The great low-frequency deception

'Fantastic, true sounding bass: these small monitors tell you exactly what is on the recording' – a statement typical of what you read in many advertisements, but it is often far from the truth. In fact it cannot be true says PHILIP NEWELL. At realistic monitoring levels, the low frequency response of small loudspeakers cannot be as accurate in terms of frequency response and transient response as a good large monitor system, flush-mounted in the front wall of a well-controlled room.

MOVING COIL LOUDSPEAKERS in boxes are volume-velocity sources. The acoustic output is the product of the area and the velocity of the diaphragm, so for any given output either a large volume of air can be moved slowly, or a small volume of air can be moved quickly. For a given frequency and SPL a large diaphragm does not need to move as fast or as far as a small one. The smaller loudspeakers need longer throw, faster-moving cones, but the restricted volume of the air inside the smaller boxes experiences a much greater pressure difference between the extremes of the cone excursion than would be the case in a larger box.

Let us say that the diaphragm of a 15-inch woofer in a 500-litre box moved 2mm peak to peak. With diaphragm radius of 6.5-inches, or 160mm, the radiation area would be 80,000 mm^2. Moving 2mm peak to peak means moving 1mm from rest to the peak in either direction, so the unidirectional displacement would be 80,000mm^2 x 1mm or 80,000mm^3. This is equal to 0.08 litres, so the static pressure in a 500-litre box would be compressed (if the cone went inwards) by 0.08 litres, or by one part in 6250 of the original volume.

For the same SPL, a 6-inch (150mm) loudspeaker in a 10-litre box would still need to move the same amount of air. However, with an effective piston radius of 2.5-inches, or 65mm, the cone travel would need to be about 12mm peak to peak, so the cone would also need to travel six times faster than the cone of the 15-inch loudspeaker. What is more, the displacement of 80,000mm^3 (0.08 litres) in a box of only 10 litres would represent a pressure change in the box of one part in 125 of the original volume. The air compression inside the box would therefore be 50 times greater than that in the 500-litre box, and there are several consequences of these differences.

Anybody who has tried to compress the air in a bicycle pump with a finger over the outlet will realise that air makes an effective spring. They will also know that the more the air is compressed, the more it resists the pressure. The force needed to compress the air by each subsequent cubic centimetre increases with the compression, so the process is not linear.

In the case of the 15-inch and 6.5-inch cones, the small cone in the small box would have a much harder job to compress the air by 1/125th of its volume than the large cone in the large box, which only needs to compress the air by a 1/6250th part in our previous example. Large boxes therefore tend to produce lower distortion at low frequencies, because the non-linear air compression is proportionally less. The concept is shown diagrammatically in Figure 1.

The non-linearity of the air spring can be better understood when you consider that it would take an infinite force to compress 1 litre of air to zero volume, yet it would take only a moderate force in the opposite direction to rarefy it to 2 litres. The forces needed for a given change in air volume (in this case +/- 1 litre) are thus not equal, so the restoring forces applied by the air on the compression and rarefaction half cycles of the cone movement are also not equal.

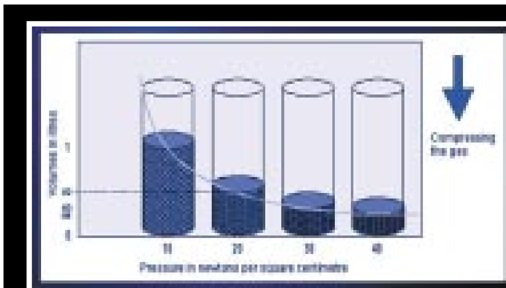

Fig. 1. Each pressure change of 10 newtons produces progressively less change in the volume of the gas. It's not linear and can give rise to harmonic distortion.

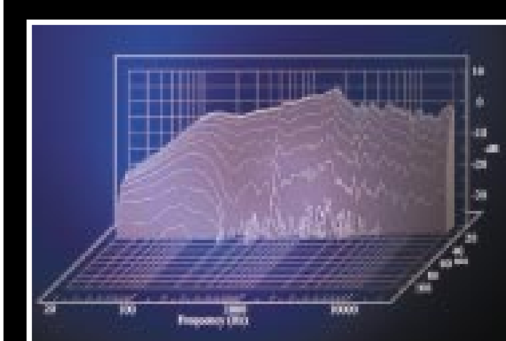

Fig. 2. Waterfall plot of a small, sealed box loudspeaker: the NS10M.

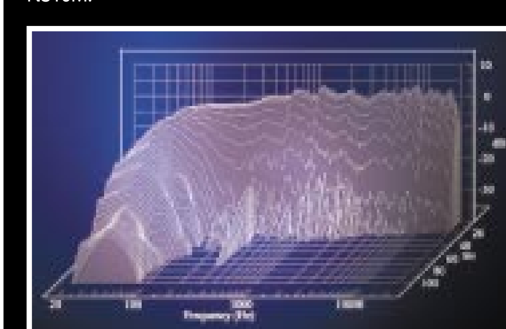

Fig. 3. Waterfall plot of a small reflex (ported) enclosure of similar size to that in Fig. 2.

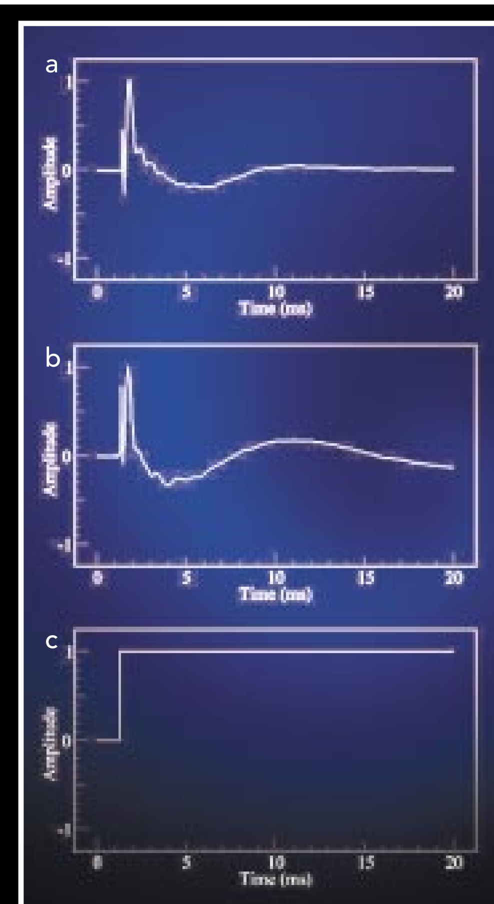

Fig. 4. Step function responses of the loudspeakers measured in Figures 2 and 3. Plot c) shows the electrical input signal to which the loudspeakers are responding. Note how rapidly the NS10 returns to a flat line on the zero amplitude axis.

The non-linear air-spring forces thus vary with the degree of displacement and also with the direction of the displacement. Changing air temperature inside the boxes also adds more complications with waste heat from the voice coils.

The main controlling factor for the extension of the low frequency response of a loudspeaker is its resonant frequency, because the low frequency response of any conventional loudspeaker system will begin to fall off quite rapidly below the resonant frequency. The resonance is a function of the stiffness of the air spring formed by the air inside the box, coupled with the moving mass of the loudspeaker cone/coil assembly. The fact that air inside a small box presents a stiffer spring than air in a larger box, for any given air displacement, means that it will raise the resonant frequency of any driver mounted in it; compared to the same driver in a larger box (i.e. loaded by a softer spring).

The only way to counter this effect, and to lower the resonant frequency to that of the same driver in a larger box, is to increase the mass of the cone/coil assembly. (Imagine a guitar string; if it is tightened, the pitch will increase. Maintaining the same tension, the only way to lower the note is to thicken the string, i.e. make it heavier.)

To move the heavier cone to displace it by the same amount as a lighter cone in a larger box, more work must be done, so more power will be needed from the amplifier. The sensitivity of a heavy cone in a small box is therefore less (for the same resonant frequency and bass extension) than for a lighter cone in a larger box. Therefore, for any given drive unit, as the box size decreases, the bass extension must also decrease. As previously stated, increasing the mass of the moving parts can restore the bass extension, but the sensitivity will reduce. There is currently no way out of this dilemma.

However, larger boxes often tend to use larger drive units and a large diaphragm will tend to be heavier than a smaller one and the diaphragm may also need to be heavier to maintain its rigidity. This would suggest a lower sensitivity in free air, but a larger magnet system can easily restore the sensitivity.

In a small box, the greater pressure changes may also require a heavier cone (so as not to deform under high-pressure loads) and the efficiency can again reduce. A bigger magnet could be an answer but it may reduce the internal volume of the box, hence stiffening the spring more and raising the resonant frequency, which may, or may not, be offset by the extra weight of the cone.

Let us consider two loudspeakers of similar frequency range but very different size. A large loudspeaker, such as the double 15-inch woofered Urei 815 driven by 1 watt would give the same SPL at 1 metre as a small loudspeaker, such as the ATC SCM10, driven by almost 200 watts. There is a currently unbreakable connection between box size, low frequency extension, and sensitivity. Reducing the box size demands that the low frequency response will be reduced or the sensitivity will be reduced. If the sensitivity is to be increased, then the box size must be increased or the low frequency extension must be reduced. High sensitivity and good low frequency extension can only be achieved in large boxes.

If the ATC seeks to achieve a good low frequency extension in a small box, then the sensitivity must be low. The ATC SCM10 has a box volume of about 10 litres; the Urei 815 contains almost 500 litres. Given that they cover the same frequency range, a sensitivity difference of about 22dB is the result.

When small cones move far and fast, they also tend to produce more Doppler distortion (or frequency modulation), and this problem is often exacerbated by the small woofers being used up to higher frequencies. Long cone excursions also mean more movement in the cone suspension systems and the restoring forces are rarely uniform with distance travelled. This tends to give rise to higher levels of intermodulation and harmonic distortion than would be experienced with a larger cone, of similar quality, moving over shorter distances.

The larger movements also require greater movement through the static magnetic field of the magnet system, which tends to give rise to greater flux distortion and even more audible non-linear Bl profile distortions. Furthermore, the reduced sensitivity of the smaller boxes means that more heat is expended in the voice coils compared to that produced in the voice coil of larger loudspeakers for the same output SPLs. This problem is aggravated by the fact that the smaller loudspeakers have greater problems in dissipating the heat. The hotter the voice coil gets, the more its resistance increases and the less power it can draw from the amplifier for any given output voltage. The resulting power compression produces yet more distortion products.

It can clearly be seen that the distortion mechanisms acting on small loudspeakers are far greater than those acting on similarly engineered large loudspeakers.

However, the market demands more output of a wider bandwidth from ever-smaller boxes, so manufactures try to rise to the challenge. One example of a technique used to augment the low frequency output is to use a reflex-loaded cabinet, with one or more tuning ports. In these systems, the mass of air inside the ports resonates with the spring that is created by the air trapped within the cabinet. If the resonant frequency is chosen to be just below where the driver response begins to roll-off, then the overall response can be extended. The resonance in the tuning port(s) takes over where the driver begins to lose its output.

This effective extension of the low frequency response also increases the loading on the rear of the driver as resonance is approached. This helps to limit the cone movement and to protect the drivers from overload. Unfortunately, once the frequencies pass below resonance the air merely pumps in and out through the ports and all control of the cone movement by the air in the cabinet is lost. In many active systems, electrical filters are used to sharply reduce the input power to the driver below the cabinet resonance frequency. This enables higher acoustic output from the loudspeaker systems, within their intended bandwidth of use, without the risk of overload and mechanical failure due to high levels of programme below the resonance. By such means, a flat response can be obtained to a lower frequency than with a sealed box of the same size, and the maximum SPL can be increased without risking drive unit failure. There is a price to be paid for these gains.

It must be understood that a resonant system can't start or stop instantly. The time response of reflex loaded loudspeakers therefore tends to be longer than that of similar sealed box versions. This means that transients will be smeared in time. The impulse response will be longer. Moreover, the effect of the electrical high-pass filters is to further extend the impulse response, because the electrical filters are also tuned, resonant circuits. In general, the steeper the filter slope for any given frequency, the longer it will ring.

More effective protection therefore tends to lead to greater transient smearing. Figure 2 shows the low frequency decay of a sealed box loudspeaker, with its attendant low frequency roll off. Figure 3 shows the low frequency response of an electrically protected reflex cabinet of somewhat similar size. Clearly the response shown in Figure 3 is flatter until a lower frequency, but a flat frequency response is not the be-all and end-all of loudspeaker performance. Note how the response between 20Hz and 100Hz has been caused to ring on, long after the higher frequencies have decayed.

Figure 4 shows the corresponding step-function responses, and Figure 5 the acoustic source plots. These plots clearly show the time response of the reflex cabinets to be significantly inferior to the sealed boxes. The low frequencies from the reflex enclosure arrive later, and take longer to decay, which compromises the 'punch' in the low frequency sound.

A sealed box cabinet will exhibit a 12dB per octave roll-off below resonance, but a reflex enclosure will exhibit a 24dB/octave roll-off, as the port output becomes out of phase with the driver output. As the system roll-offs are often further steepened by the addition of electrical protection filters below the system resonance, sixth, and even eighth order roll-offs (36dB and 48dB per octave, respectively) are quite common. With such protection, some small systems can produce high output SPLs at relatively low frequencies, but the time (transient) accuracy of the responses may be very poor.

Inevitably, the different resonances of the different systems will produce musical colourations of different characters and such inconsistency of colouration does little to help the confidence of the users in studios. If a mix sounds different when played on each system, then how do you know which loudspeaker is most right or when the balance of the mix is correct?

The tendency is that well-designed sealed-box cabinets sound more similar to each other than do small reflex-loaded boxes. The resonances of the sealed boxes tend to be better controlled, and are usually much more highly damped than their reflex-loaded counterparts. This leaves the magnitude of the frequency response of sealed boxes as their predominating audible characteristic, but it is usually the time responses of reflex enclosures that give rise to their different sonic characters.

There is considerable evidence to suggest that the use of Auratones and Yamaha NS10Ms has been due to their rapid response decays. A roll-off in the low frequency response of a loudspeaker used for mixing is in itself not a great problem, because any wrong decisions can usually be corrected by equalisation at a later date, such as during mastering.

An error in the time response, such as that added by tuning port and filter resonances, can lead to misjudgements, especially between percussive and tonal low frequency instruments, which cannot be adjusted once they have been mixed together.

A problem therefore exits in terms of how we can achieve flat, uncoloured, wide-band monitoring at relatively high sound pressure levels from 10-litre boxes. At the moment, the answer is that we cannot do it. Just as there is a trade-off between low frequency extension, low frequency SPL and box size; there is also a trade-off between low frequency SPL, bass extension, and transient accuracy if bass reflex loading and electrical protection are resorted to in an attempt to defeat the box size limitations.

In fact, at low SPLs, good low frequency extension can be achieved from small boxes, but the non-linearity of the internal air-spring leads to high distortion when the cone excursions, and hence high degrees of internal pressure changes, become significant. Also, in a small sealed box, there is the problem of how to get rid of the heat from the voice coil. Thermal overload and burnout is always a problem at high SPLs due to the high power necessary to overcome the problem of the poor system efficiency. This leads to the thermal compression that limits the output dynamics from accurately following the dynamics of the input signal.

From the waterfall plots of Figures 2 and 3 it can be seen that the decay is never instantaneous, and that there is a slope to the time representation (although at low frequencies some of this can be due to the time response of the measurement filters). The question has often been asked whether a flattening of the low frequency response would inevitably lengthen the time response, even with the sealed boxes. In truth, the tendency is for the flattening of the amplitude response to shorten the time response, by means of its correction of the phase response errors that are associated with the roll-off.

This means that a large or small sealed box, equalised or not, would still exhibit a much faster time response than a reflex enclosure. Figures 6 and 7 show the comparative effect. What is very significant is that an enormous number of music recording professionals, by opting for NS10s, Auratones and others of similar response characteristics, have indicated their preference for time response accuracy over absolute frequency response accuracy.

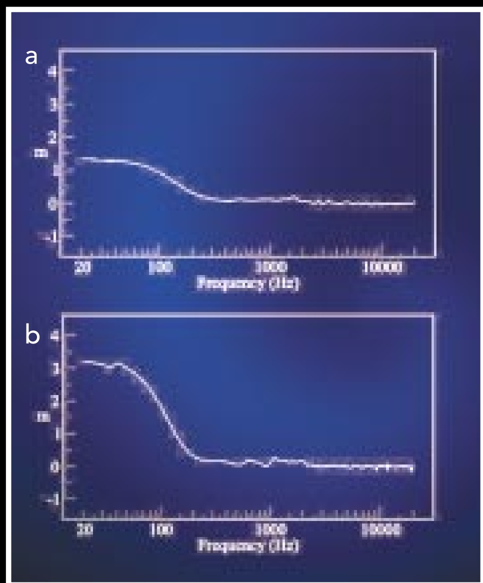

Fig. 5. Acoustic source plots corresponding to the step-function plots of Figure 4. The low frequency response delay is shown in terms of from how many metres behind the loudspeaker the low frequencies are apparently emanating. As each metre corresponds to about 3ms, it can be appreciated how the low frequencies from the sealed box, a), arrive much more 'tightly' with the rest of the frequencies than from the reflex loaded box.

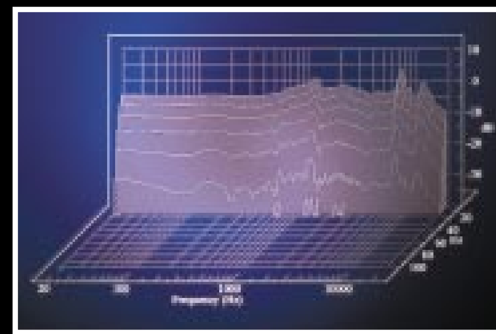

Fig. 6. Waterfall plot showing the effect on the time response of electrically flattening the response of an Auratone. Although the response is flatter down to a lower frequency than the reflex loaded enclosure shown in Figure 3, the time response is still much quicker - the decay is much more rapid. Such equalisation is not a practical solution because the loudspeaker would overload badly even at low SPLs.

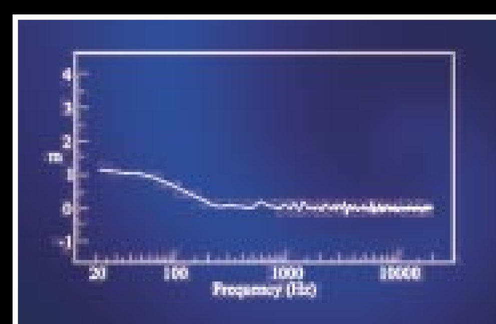

Fig. 7. Acoustic source plot for a 700 litre, wide-range, flush-mounted, studio monitor system. Note how the NS10M's response (Figure 5a) mimics that of this large monitor system.

Many mastering engineers concur with this choice, citing low distortion and good transient accuracy as being more important to them than absolute frequency response flatness. (Strictly speaking, we should be speaking about the pressure amplitude response, or the modulus of the frequency response, because the term 'frequency response' technically also includes the phase response, but I will stick to the popular term here.)

The whole close-field concept of monitoring seems to have been borne out of a recognition that the monitoring of the direct sound has been more reliable than monitoring the direct/room-sound combination from the wider-range large monitors. Many studio designers now aim for highly absorbent control rooms, which can maintain the direct sound from the main, flush-mounted monitors, all the way to the mixing console and beyond. Contrary to a popular fallacy, these rooms are not oppressive to be in, because reflective surfaces are positioned in the rooms in places where they cannot affect the monitoring, but they give life to the speech of the occupants. This is probably the only way to deliver flat, full-frequency range, fast time-response monitoring, because current technology cannot supply this from small boxes.

There are those who say that very fast time responses are not necessary from small loudspeakers, because their decay times are still shorter than many of the rooms in which most of them will be used. However, what they fail to realise is that the small loudspeakers are usually being used in the close-field, which is normally considered to be within the critical distance where the direct sound and room sound are equal in level. It therefore follows that if one is listening in the close-field, then the responses of the loudspeakers will predominate in the total response. Indeed, this is the principal reason for the use of close-field monitoring.

A great deal of illogical thinking, lack of awareness of the facts, and a legacy of continuing to look at traditionally measurable aspects of loudspeaker design, has led to the manufacture of loudspeakers that seek to respond to the traditional response norms. This is despite the fact that many recording professionals have opted for loudspeakers whose responses did not comply with the perceived technical requirements. They have chosen to use loudspeakers that they found reliable to work with, either despite or in total ignorance of their published response plots.

It must be added that much ignorance of the facts also exists within many loudspeaker manufacturing companies, where the people responsible for defining what is produced are not loudspeaker engineers or sound engineers. In many cases they are simply business people. So, with no clear signals from the recording industry about what it needs, the businesses produce what they think they can sell most of. If this means a battle to improve some largely irrelevant specifications, then this is the path they pursue. This has led to the state of affairs in which chaos rules in the low frequency responses of current small 'monitor' loudspeakers. Improving the time responses of many small monitor loudspeakers is a long overdue priority. ■