Proceedings of the Institute of Acoustics

STEADY STATE AND TRANSIENT LOUDSPEAKER FREQUENCY RESPONSES

Keith Holland ISVR, University of Southampton, UK
Philip Newell Consultant, Spain
Peter Mapp Peter Mapp & Associates, UK

1. INTRODUCTION

Probably the most important and well-known specification for a high quality loudspeaker is its frequency response. Most audio professionals and enthusiasts are quite used to using frequency response plots to make judgements as to the likely quality of sound reproduced by loudspeakers. This importance comes from linear systems theory which tells us that the response of a loudspeaker to *any* signal (within reasonable limits) can be accurately predicted from the frequency response alone.

A major goal in the design of high quality loudspeakers is therefore to achieve a frequency response which evenly covers as much of the audio frequency range as possible. At the high-frequency end of the spectrum, this goal is readily achievable, with many modern high frequency loudspeakers having excellent responses up to frequencies well beyond the audible limit for humans; however, achieving an extended response at low frequencies is always subject to much compromise.

References [1, 2] consider the design of monitor loudspeakers, and conclude that the success of a few well known loudspeakers for this application may in part be attributable to the low-frequency alignment. This paper builds on that work, by taking a look at the compromises involved in extending the low-frequency response of loudspeakers and the likely audible consequences of these compromises. The low-frequency responses of a number of commercially-available loudspeakers are studied, and a comparison is made between the steady-state responses and the time-related responses of the loudspeakers.

2. THE LOW FREQUENCY RESPONSE COMPROMISE

In nature, we tend to associate low frequency sounds as only emanating from large objects — small objects are inherently inefficient radiators of low frequencies. Thus a loudspeaker which can *easily* reproduce very low frequencies is necessarily very large — or very quiet. The frequency range of the human auditory system is generally accepted to be from 20Hz to 20kHz, so it may be reasonable to expect the response of a loudspeaker to extend down to, or beyond 20Hz. It is worthwhile, at this stage, to put this requirement in perspective. Table 1 shows the wavelength of a range of low frequency tones, along with audible threshold and normal, speech-type, loudness levels (60 Phon). Also included are the peak−to−peak displacements required of a 6 inch diameter (150mm) and a 15 inch diameter (340mm) loudspeaker to reproduce the tones at speech loudness at 2m distance under free-field conditions.

Frequency (Hz)	Wavelength (m)	Threshold (dB SPL)	Speech Level (dB SPL)	*X* (6") (mm)	*X* (15") (mm)
100	3·4	25	67	0·6	0·08
70	4·9	32	72	2	0·4
50	6·8	40	77	8	1·2
35	9·8	55	85	38	6
20	17·5	72	100	660	100

Table 1 The wavelength, audible threshold level, speech loudness level and loudspeaker displacements (X) necessary to achieve speech loudness levels for various low-frequency tones

An obvious conclusion from Table 1 is that as the frequency reduces, the demands on the loudspeaker displacements increases rapidly. It is clearly impractical for a 6 inch loudspeaker to reproduce 20Hz under free-field conditions (it requires > 25mm displacement to be audible at all), and barely practical for a 15 inch loudspeaker (4mm for threshold). It should be noted that these requirements are relaxed when more than one loudspeaker is present [3] and / or the loudspeakers are radiating sound into a room.

The figures above suggest that attempting to reproduce very low frequencies using all but the largest loudspeakers will give rise to displacement-related problems. To overcome this, it is usual to limit the low frequency response of practical loudspeakers by either electro-mechanical or electrical means. This does seem reasonable, at least for the reproduction of speech and most music signals, as these contain very little information at very low frequencies. For a loudspeaker with a sealed cabinet, the displacement is essentially constant below the bass resonance frequency — the lower the resonance frequency, the greater the maximum displacement — so designing this frequency to be higher than that required for reproducing very low frequencies automatically reduces the displacement, and hence the output, at these frequencies. Things are less clear when bass reflex porting is used however. In this case the displacement of the driver is reduced at the port tuning frequency but increased at lower frequencies to approximately that set by the free-air resonance of the driver, which is lower than the same driver in a sealed cabinet.

When a loudspeaker is to be driven to high levels, such as is often the case with studio monitors, it is essential that the low frequency displacement is kept within limits set by excessive signal distortion and / or damage. To this end, many high power loudspeakers employ high-pass protection filters designed to filter out the very low frequencies. Thus a number of different low frequency alignments can be employed in the design of low frequency loudspeakers to trade-off between low frequency extension and displacement protection. Table 2 lists some of the alignments encountered in modern high power loudspeakers.

Description	Roll-off order
Sealed box	2nd
Sealed box with 1st order filter	3rd
Damped port	3rd
Damped port with 1st order filter	4th
Ported	4th
Sealed box with 2nd order filter	4th
Damped port with 2nd order filter	5th
Ported with 1st order filter	5th
Ported with 2nd order filter	6th

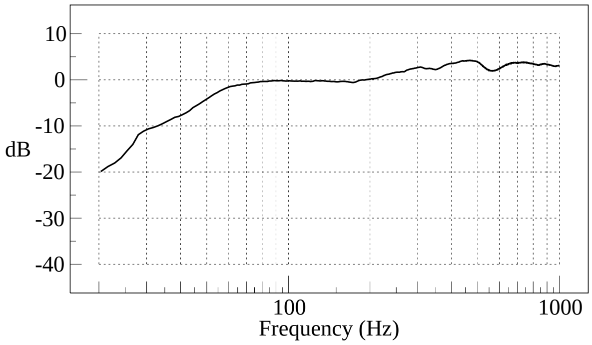
Table 2 Some Common Low-Frequency Alignments and their Associated Roll-off Slopes

Considering the different roll-off slopes, similarly-sized loudspeakers with different alignments will respond differently to different signals; it therefore seems likely that they will also sound different.

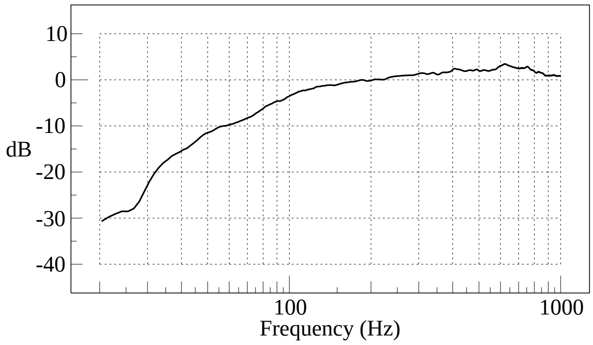
3. THE LOW-FREQUENCY RESPONSE OF SOME LOUDSPEAKERS

In this section, the low-frequency response of 10 different loudspeakers will be studied. All of the loudspeakers are similar in size, but they employ a variety of different low-frequency alignments. Some use passive, high-level crossovers, whilst others are fully active, with built-in amplifiers including protection circuitry etc. All of the loudspeakers were measured under near-identical conditions in the large anechoic chamber at ISVR. Figures 1.1—1.10 shows the magnitude of the frequency response of the 10 loudspeakers from 20Hz to 1kHz, along with brief descriptions of the type of low-frequency alignment. The loudspeakers are referred to by number, rather than make or model. Despite all of the loudspeakers being of similar physical size, the amount of low frequency extension achieved in the 10 different designs varies considerably; for example, loudspeakers #1 and #3 are 10dB down at 30Hz, whereas loudspeaker #2 is 10dB down at 55Hz.

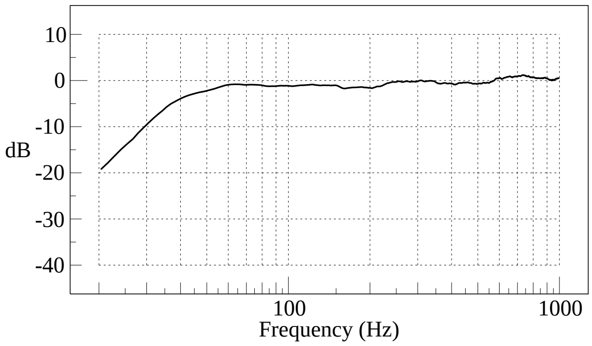
Figures 1.1—1.10 Low-Frequency Response of Example Loudspeakers



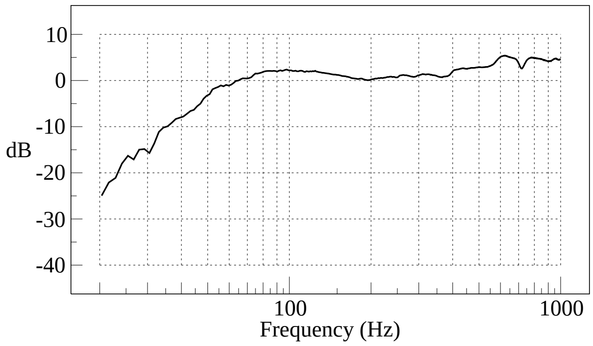
#1 Sealed: 2nd Order



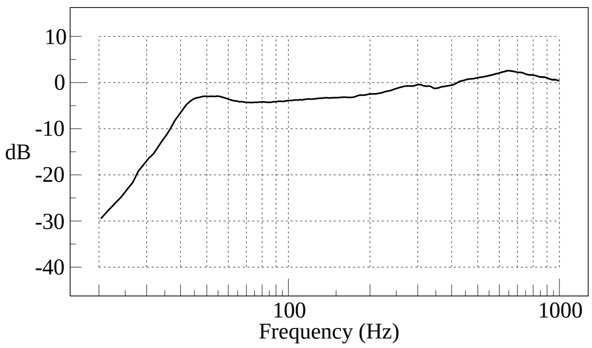
#2 Sealed: 2nd Order



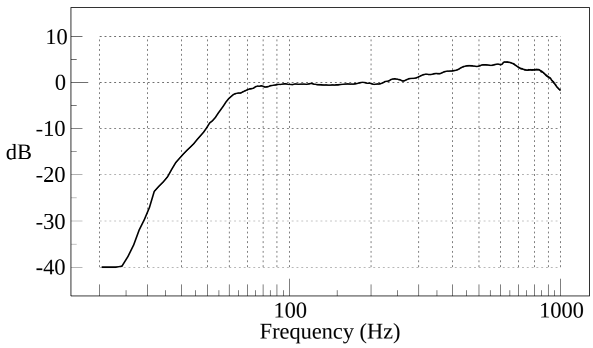
#3 Sealed with Filter: 3rd Order



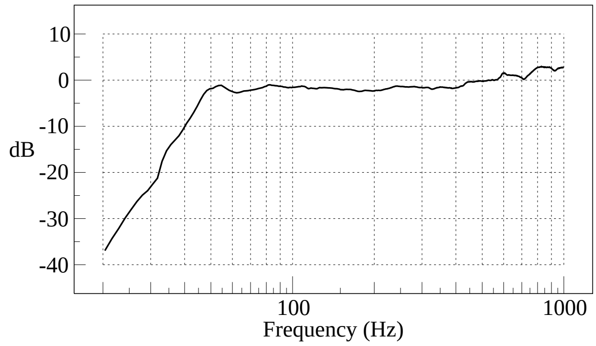
#4 Ported: 3rd Order



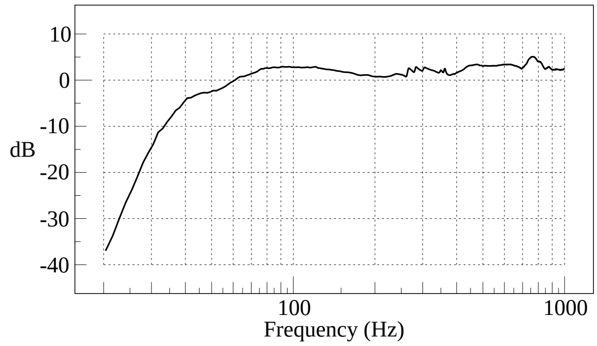
#5 Ported: 4th Order



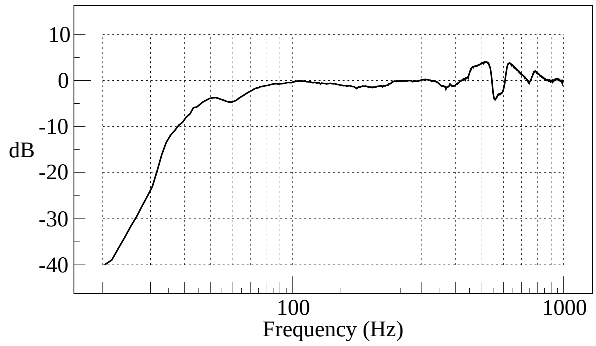
#6 Ported with Filter: 5th Order



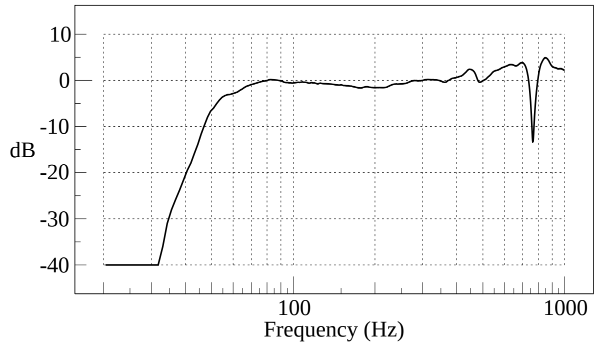
#7 Ported with Filter: 5th Order



#8 Ported with Filter: 6th Order



#9 Ported with Filter: 6th Order

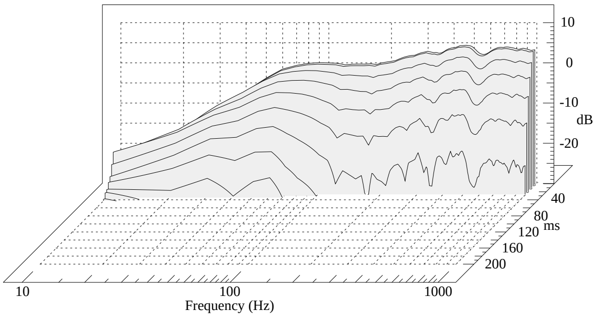


#10 Ported with Filter: 8th Order

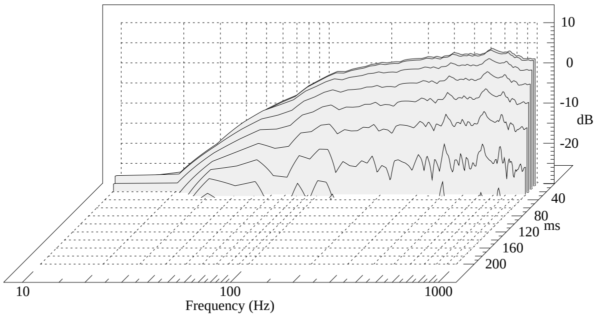
From Figure 1, it is tempting to assume that the response of all of these loudspeakers to signals having frequencies at, or above, the roll-off frequencies will be similar as they all respond to these signals at similar levels. However, different low-frequency alignments give rise to different phase responses, even at frequencies above the roll-off. Figures 2.1—2.10 show waterfall plots for the loudspeakers which are the result of displaying the Fourier transforms of short duration, windowed sections of the loudspeaker impulse responses on time / frequency / level plots.

The waterfall plots in Figure 2 show that those loudspeakers with higher order roll-offs tend to 'hang on' or 'ring' at around the roll-off frequency whereas those with lower order roll-offs do not. There are some possible audible consequences to this when considering transient signals. Transient signals, by definition, are short duration signals that contain a wide range of frequencies. The start and the end of musical notes close in frequency to the roll-off frequency will excite the ringing which in turn causes the musical note to change frequency to that of the ringing frequency. This may give rise to the “one-note-bass” subjective criticism levied at some loudspeakers. To demonstrate this, Figures 3.1—3.10 show waterfall traces of 4 cycles of a 60Hz tone reproduced by the loudspeakers. These plots are the result of convolving the tone burst with the impulse response of the loudspeakers and calculating the waterfalls as per Figure 2. The spread of frequencies at the start and end of the tone burst are clearly seen, as are the shifts in frequency as the tone decays for those loudspeakers with more rapid roll-offs.

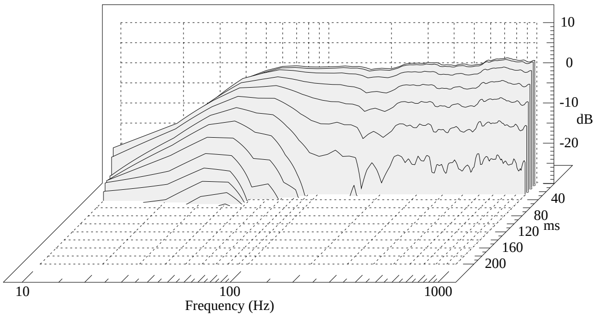
Figures 2.1—2.10 Waterfall Plots of Example Loudspeakers



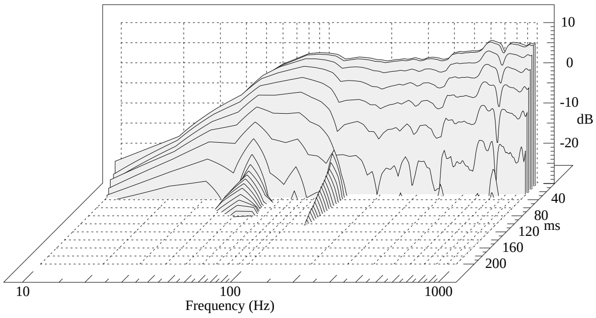
#1 Sealed: 2nd Order



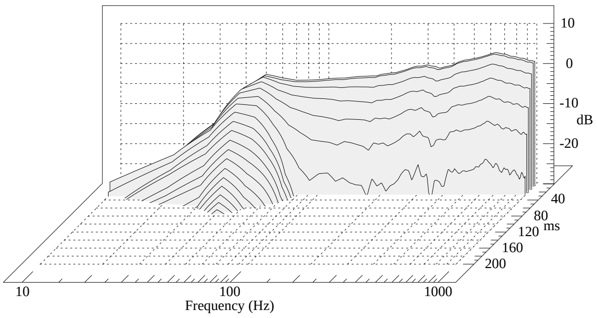
#2 Sealed: 2nd Order



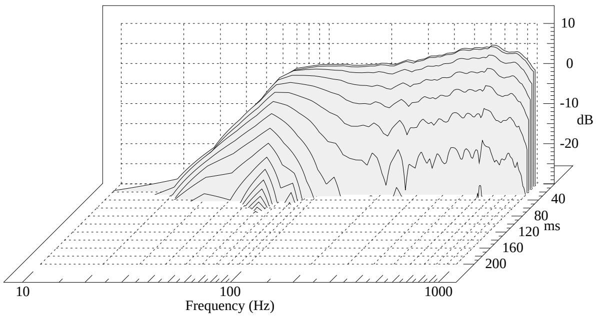
#3 Sealed with Filter: 3rd Order



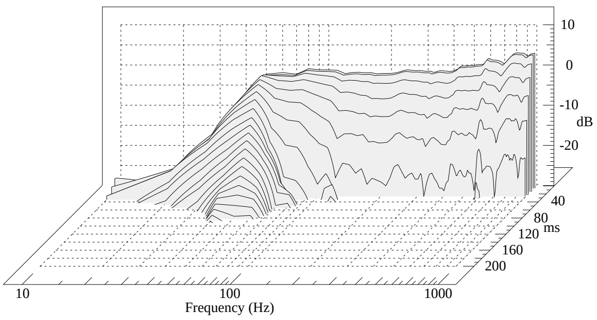
#4 Ported: 3rd Order



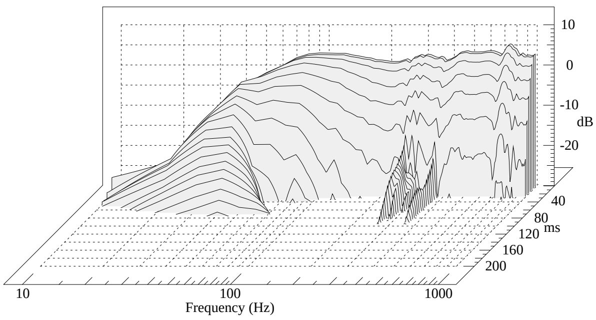
#5 Ported: 4th Order



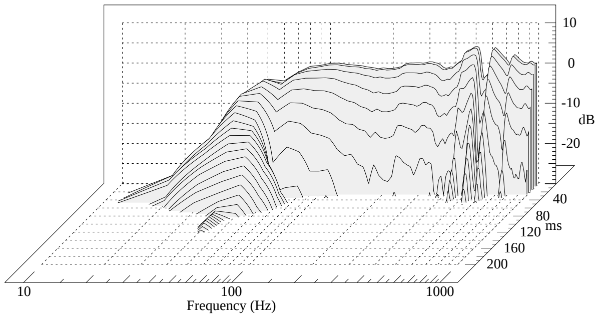
#6 Ported with Filter: 5th Order



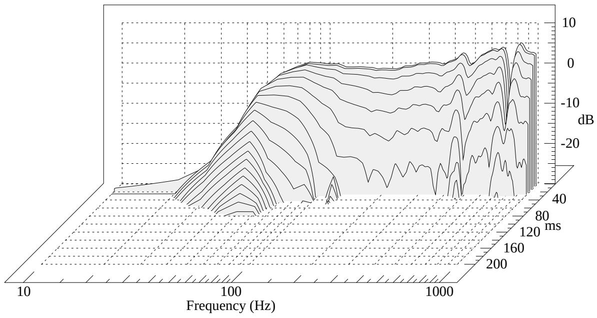
#7 Ported with Filter: 5th Order



#8 Ported with Filter: 6th Order

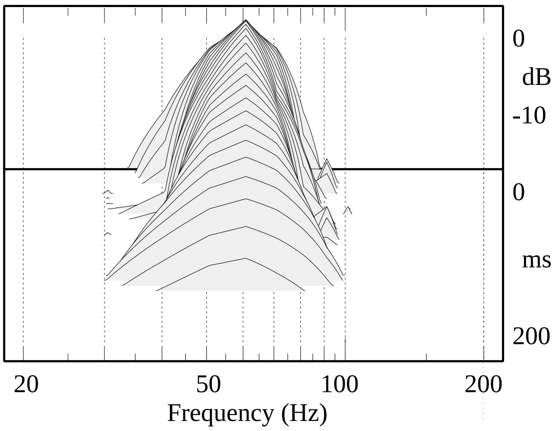


#9 Ported with Filter: 6th Order

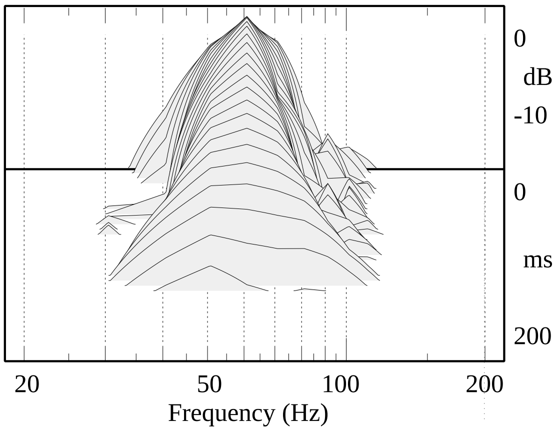


#10 Ported with Filter: 8th Order

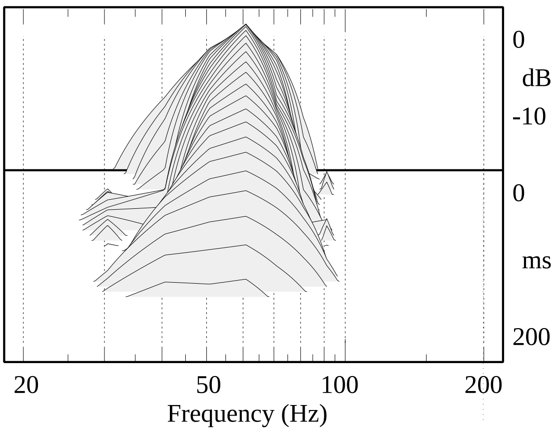
Figures 3.1—3.10 Waterfall Plots of 4 Cycles of 60Hz Tone Reproduced by Loudspeakers



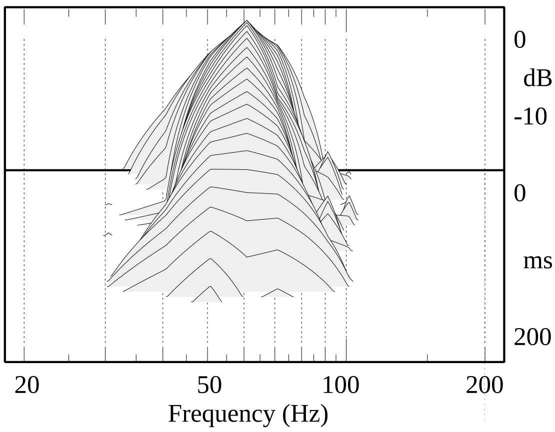
#1 Sealed: 2nd Order



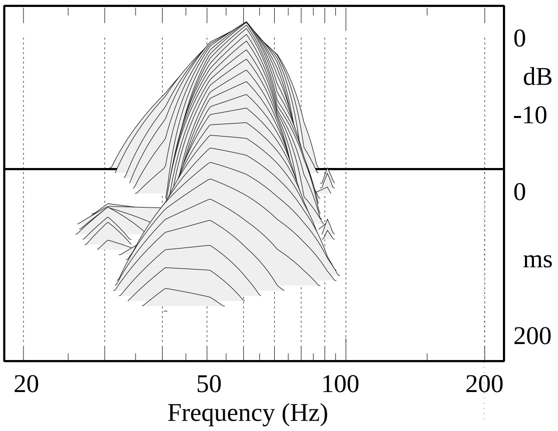
#2 Sealed: 2nd Order



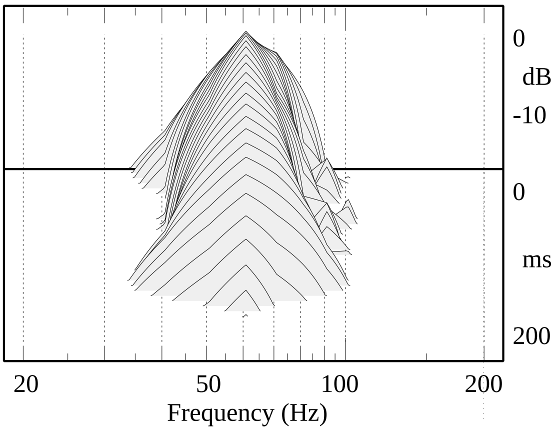
#3 Sealed with Filter: 3rd Order



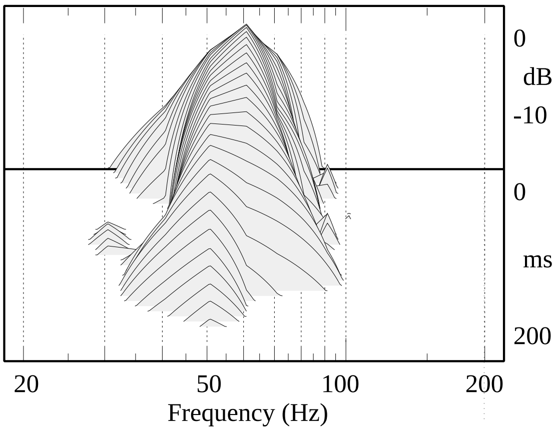
#4 Ported: 3rd Order



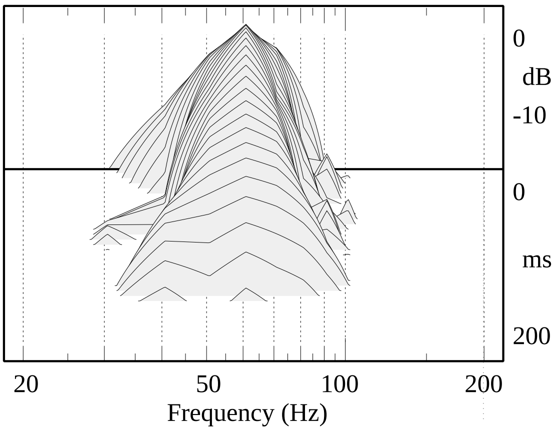
#5 Ported: 4th Order



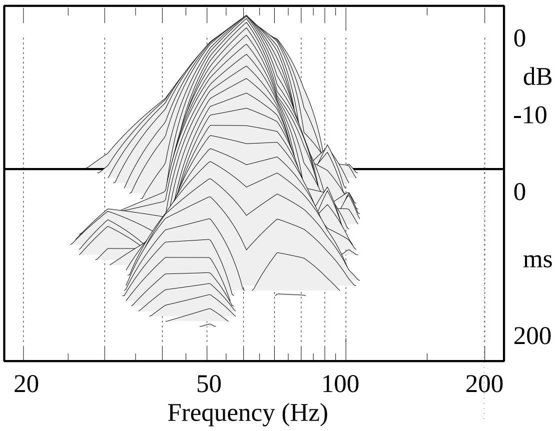
#6 Ported with Filter: 5th Order



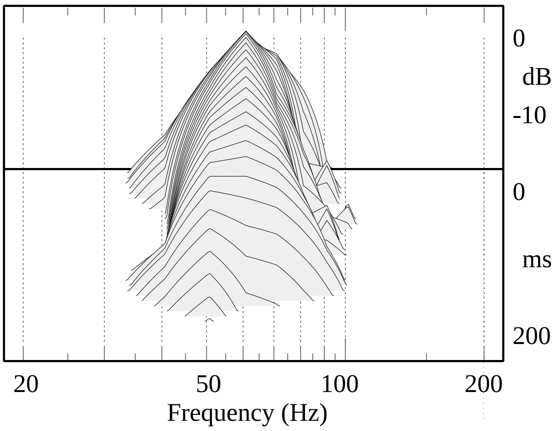
#7 Ported with Filter: 5th Order



#8 Ported with Filter: 6th Order



#9 Ported with Filter: 6th Order

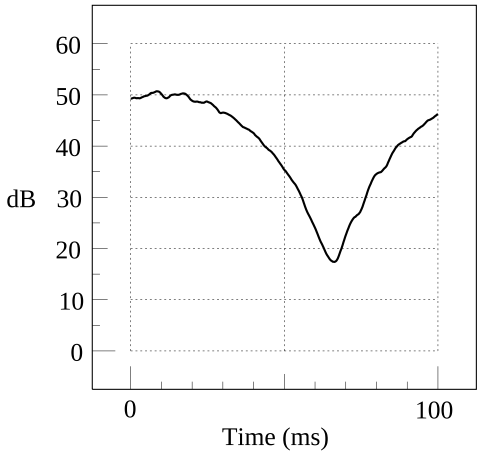


#10 Ported with Filter: 8th Order

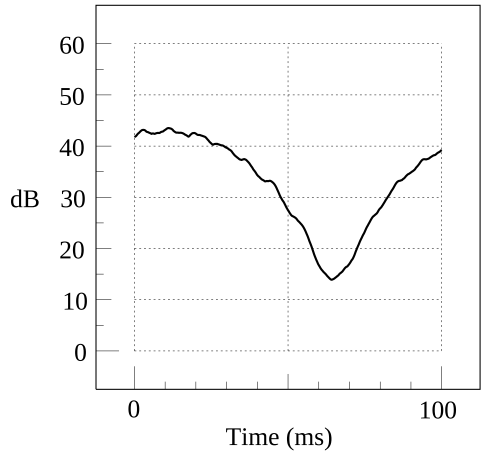
As well as the ringing affecting the apparent frequency of the start, and particularly, the end of a note, it may also serve to mask low-frequency detail. To investigate this, the impulse responses of the loudspeakers were convolved with a modulated noise signal.

The signal consists of pseudo-random noise with a bandwidth equal to the 50Hz octave band (about 35Hz to 70Hz) which is amplitude modulated by a 10Hz sine-wave. Figures 4.1—4.10 show the result of averaging the squared response to 100 cycles of 100ms of the noise after convolution with the loudspeaker responses. The process is not unlike that used to measure speech intelligibility indices (STI); the shallower the modulation, the more the loudspeaker is likely to mask low-frequency detail.

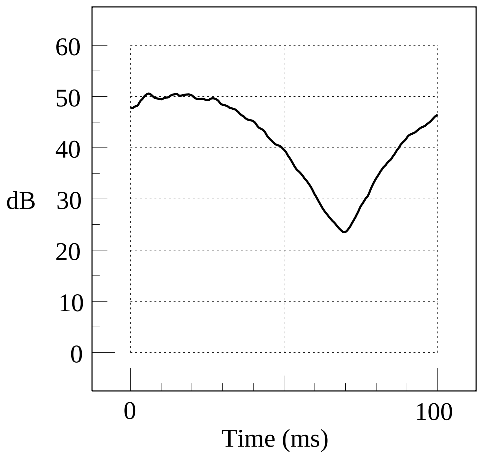
Figures 4.1—4.10 Averaged, Convolved, Modulated Noise for the Example Loudspeakers



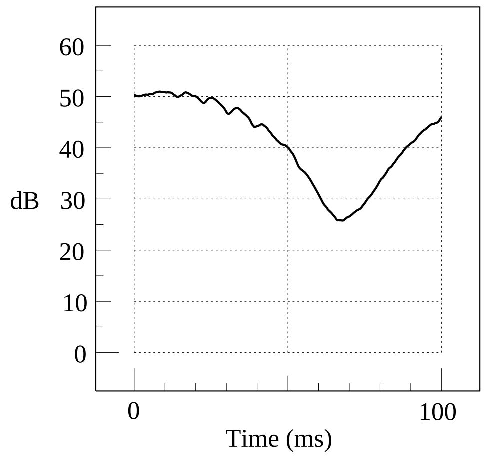
#1 Sealed: 2nd Order



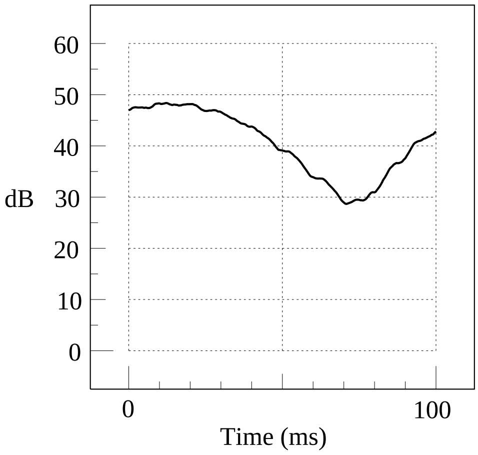
#2 Sealed: 2nd Order



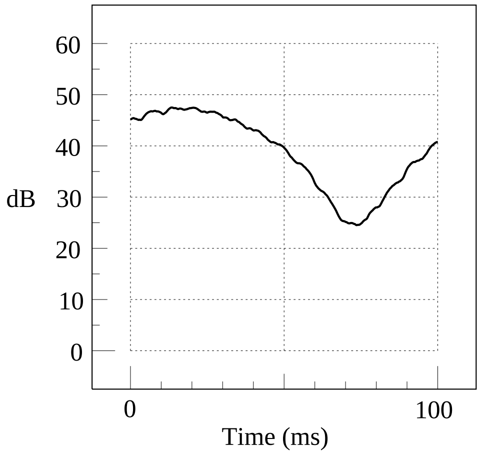
#3 Sealed with Filter: 3rd Order



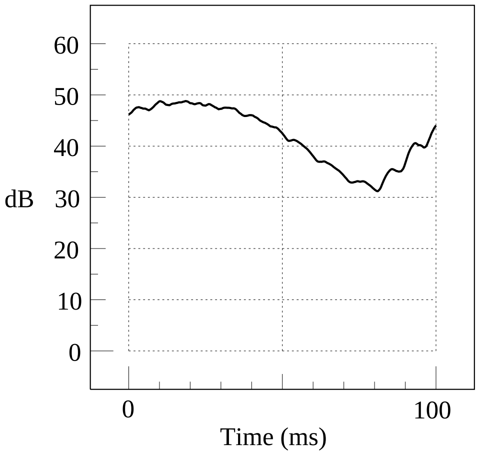
#4 Ported: 3rd Order



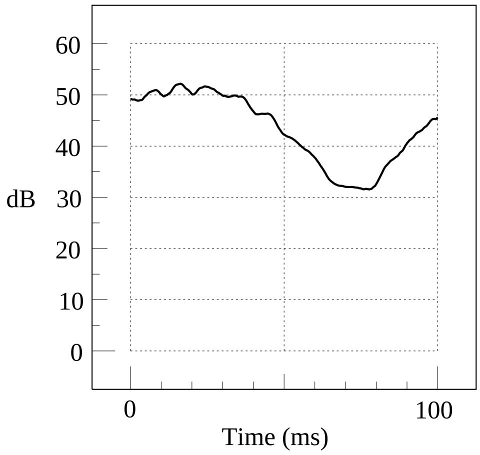
#5 Ported: 4th Order



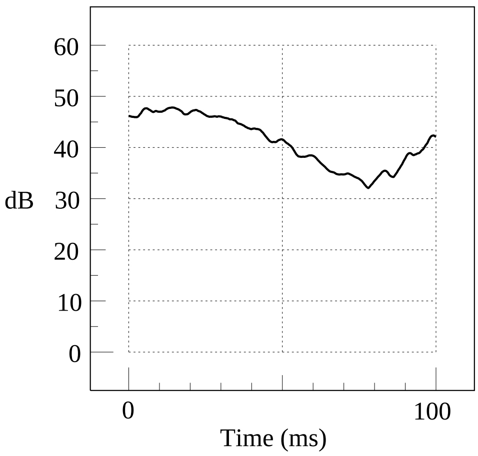
#6 Ported with Filter: 5th Order



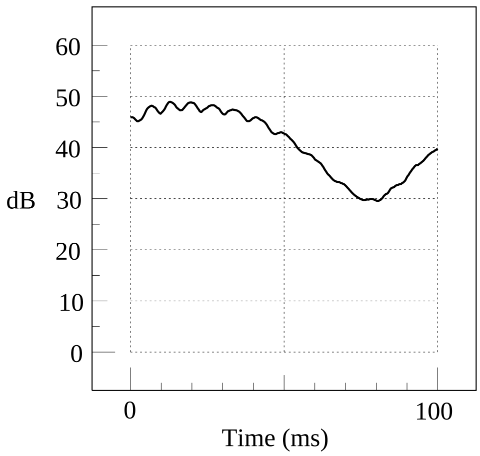
#7 Ported with Filter: 5th Order



#8 Ported with Filter: 6th Order



#9 Ported with Filter: 6th Order



#10 Ported with Filter: 8th Order

Figure 4 shows that the loudspeakers vary quite considerably in their ability to reproduce the modulations in the noise. The modulation depth for the loudspeakers varies between that for #1, with a depth of 32dB (40:1), and that for #9, with a depth of 14dB (5:1). As a general trend, as the order of the alignment increases, the modulation depth decreases.

3. APPLYING EQUALISATION TO THE LOUDSPEAKERS

Some of the loudspeakers in this group have built-in electronic crossovers and amplifiers which may include electronic filtering to tailor the low-frequency response, such as the high-pass protection filters mentioned above. It may be expected, therefore, that if all of the loudspeakers were equalised electronically to have the same roll-off, that the differences in the transient response would disappear.

The question of how successfully the response of a loudspeaker can be equalised has wider implications than just achieving an extended frequency response. Consider a pair of loudspeakers used in a studio to monitor the recording of a bass drum and bass guitar. The quantity of low frequencies in the resultant mix will depend upon the low frequency response of the monitors. When this recording is mastered, the mastering engineer corrects for any deficiencies in the low frequencies of the mix by applying electronic equalisation. This is fine, except that the relative levels of the bass drum and bass guitar in the mix will be affected by the transient response of the monitor loudspeakers. For example, a loudpeaker that has an extended low frequency response but poor transient response may yield a mix that is biased towards the bass drum, as the steady-state notes of the guitar will sound louder. The equalisation applied at the mastering stage cannot change the relative levels of the drum and guitar, so the recording is compromised. The success or otherwise of this post-equalisation therefore depends upon the degree to which the original monitoring loudspeaker themselves can be equalised.

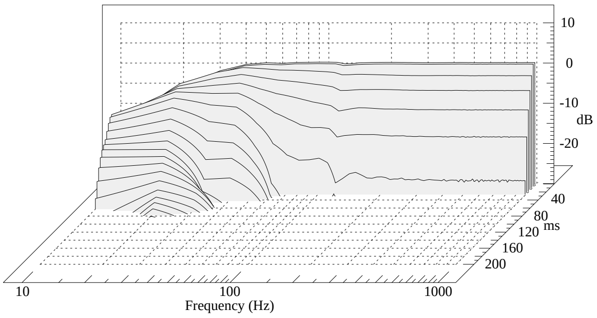
In general, the phase response of a loudspeaker can be separated into minimum- and excess-phase components. Application of a conventional, real-time filter to equalise the amplitude response will automatically equalise the minimum-phase component of the phase response, but not the excess-phase part. It is possible to separate a frequency response into the two components: a minimum-phase response which has the amplitude response of the original response and minimum phase, and an all-pass response which has unit amplitude and the excess phase; the original response is then the product of the two component responses

$$H(\omega) = |H(\omega)| \; exp\{j\phi_m\} \, exp\{j\phi_e\} \quad , \qquad (1)$$

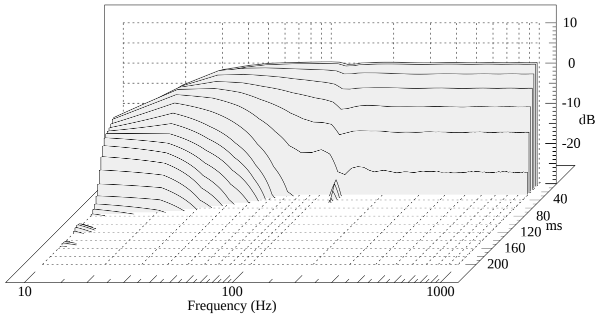
where ϕ_m and ϕ_e are the minimum and excess phases respectively. The minimum phase reponse can be calculated using the complex cepstrum: the Fourier transform of the log of the magnitude of the frequency response is truncated such that the value is zero for all negative quefrencies, and the values at all positive quefrencies are doubled. The anti-log of the inverse Fourier transform of this truncated cepstrum is then the minimum-phase response component. The excess-phase is then the division of the total response by the minimum-phase response.

The excess-phase response represents the response of a loudspeaker after equalisation by a ’perfect’ real-time filter, and thus is a measure of the success of applying such equalisation. As the excess-phase response extends ’flat’ down to 0Hz, and the measured responses are unreliable at very low frequencies, it is necessary to apply a high-pass filter to the responses. A 2nd-order filter having a turn-over frequency of 20Hz was therefore chosen as representing the response of an ideal loudspeaker. Figures 5.1—5.10 show the waterfall plots for the filtered excess-phase responses of the 10 loudspeakers.

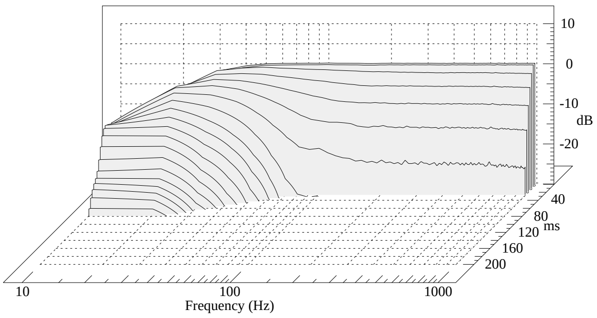
Figures 5.1—5.10 Waterfall Plots of the Excess-Phase Response of the Example Loudspeakers



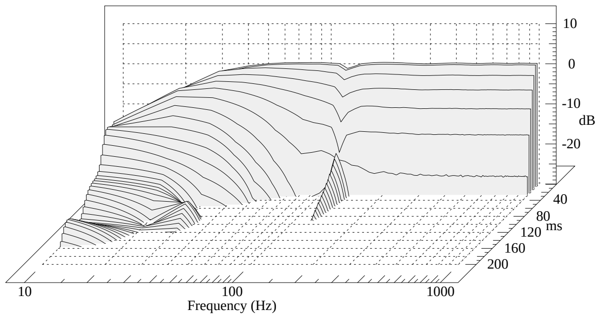
#1 Sealed: 2nd Order



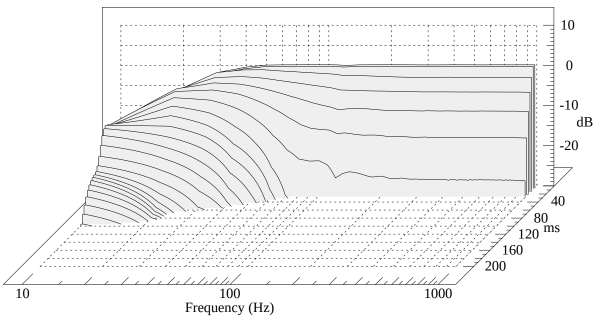
#2 Sealed: 2nd Order



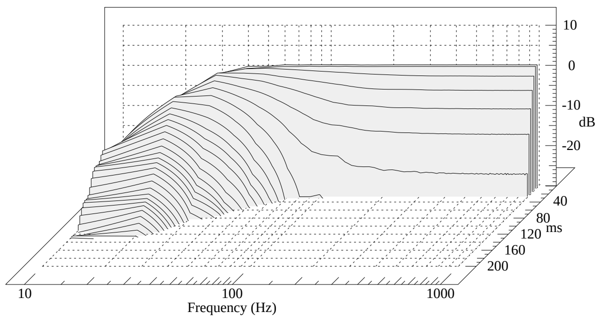
#3 Sealed with Filter: 3rd Order



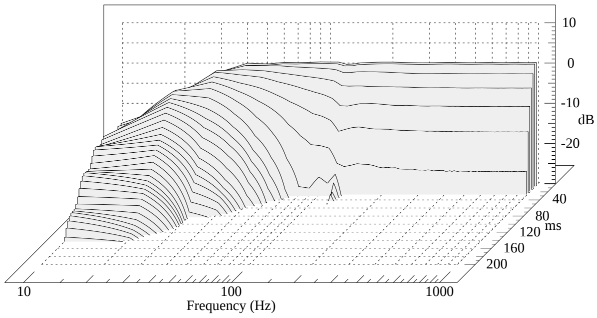
#4 Ported: 3rd Order



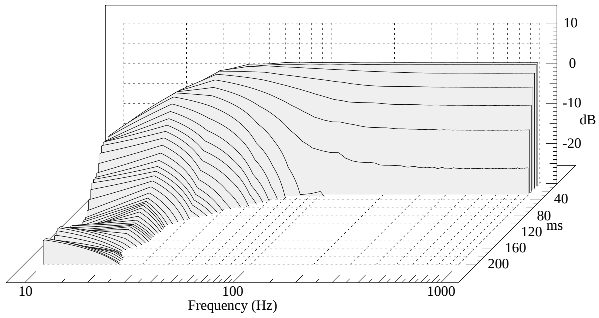
#5 Ported: 4th Order



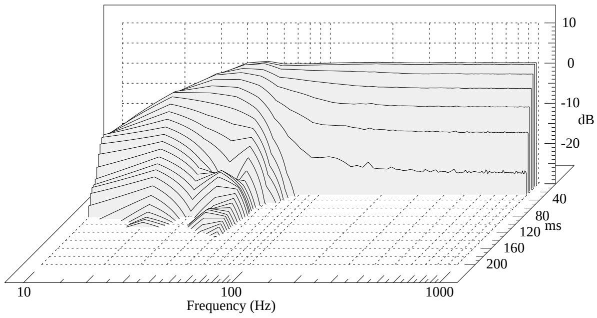
#6 Ported with Filter: 5th Order



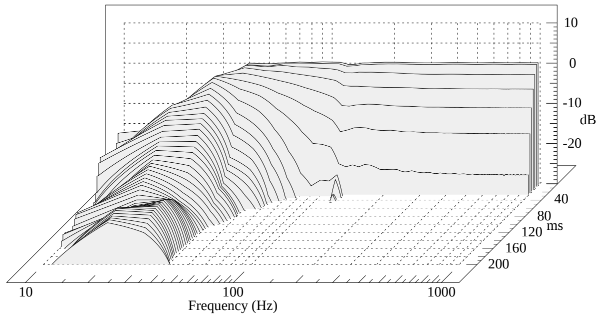
#7 Ported with Filter: 5th Order



#8 Ported with Filter: 6th Order



#9 Ported with Filter: 6th Order



#10 Ported with Filter: 8th Order

The waterfall plot for loudspeakers #1—#3 are little different to that for the 20Hz high-pass filter alone (not shown) which suggests that these loudspeakers can be equalised successfully. This implies that post-equalisation of mixes created while monitoring on these loudspeakers should be successful. The other 7 loudspeakers vary in the amount of excess phase present, with #8 and #10 standing out as particularly poor.

5. DISCUSSION

The results presented above tend to strongly suggest that there is more to an accurate low-frequency response than extending the amplitude of the frequency response flat to as low a frequency as possible. Loudspeakers with extended responses and sharp cut-offs may well sound more impressive, or ’full’, than those with higher cut-offs but lower order slopes, however, the findings of this work suggest that the response of the latter to a wide variety of programme is probably the more accurate. Clearly, loudspeakers #1, #2 and #3 exhibit much better transient responses than the other loudspeakers, and it is interesting to note that these three are all sealed-box designs, whereas all of the others are ported. Comparing the two third-order designs, the first-order protection filter applied to loudspeaker #3 does not seem to compromise the transient reponse as much as the use of a damped port in loudspeaker #4.

One important factor not studied in this paper is the degree of non-linear distortion exhibited by the various designs. Many sources of non-linear distortion in loudspeakers at low frequencies, such as suspension and magnet / coil problems, are associated with the displacement of the diaphragm, and it has long been appreciated that use of a port reduces the diaphragm displacement at, and around, the port tuning frequency. When high output levels are required from small loudspeakers, without excessive non-linear distortion, there is clearly a strong case for the adoption of a ported design. When accurate reproduction is paramount, for qality control purposes for example, then the sealed box alignment, with low-frequency enhancing filtration if required, should be the preferred choice. It is important to note here that the audibility of low-frequency distortion remains a subject requiring much further study.

Another important consideration is the low-frequency response of the various loudspeakers in rooms. The frequency below which no modes exist in a room — the pressure zone — is governed by the size of the room. For a perfectly rigid, sealed room, the pressure at these frequencies is proportional to the displacement of the diaphragm, and not the acceleration, as is the case under free-field conditions. As stated above, the displacement of a diaphragm in a sealed box is independent of frequency below the bass resonance. It follows then that a sealed-box loudspeaker will have a flat response at low frequencies in a sealed room, and that it may therefore be desirable to tune the roll-off frequency of sealed-box loudspeakers according to the size of room.

6. CONCLUSIONS

A number of conclusions can be drawn from the findings reported in this paper.

- Similar-sized loudspeakers can be designed with widely different low-frequency alignments.
- There is an important trade-off between low-frequency extension and excessive diaphragm displacement.
- Loudspeakers with low-order alignments offer more accurate transient reproduction than higher order designs.
- Loudspeakers with low-order alignments are more readily equalised than higher order designs.
- The use of a port degrades low frequency transient performance.
- Sealed box loudspeakers are capable of superior low-frequency transient performance than equivalent ported designs, but probably at the expense of higher distortion at high levels.

7. REFERENCES

[1] P R Newell, K R Holland & J P Newell, “The Yamaha NS10: Twenty Years a Reference Monitor, Why?”, PROC IOA 28(8), 2001, 29—40.

[2] P R Newell, K R Holland & P Mapp, “The Perception of the Reception of a Deception”, PROC IOA 29(8), 2002, (CD Only).

[3] K R Holland & P R Newell, “Mutual Coupling in Multi-Channel Loudspeaker Systems”, PROC IOA, 19, 1997.