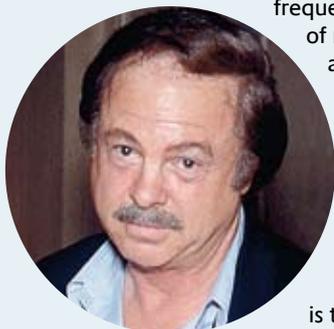


# Loud loudspeakers!

Keith Howard on designs able to deliver the true dynamics of live music

**RIGHT:** A number of manufacturers are now pursuing loudspeakers that promise to bring to our listening rooms the full SPLs of live music

**BELOW:** Arnie Nudell, creator of the Infinity IRS speaker, who until his death last year was a key player in the current PS Audio loudspeaker project



It's a common audiophile experience that listening to a powerful amplifier lends a sense of ease to sound reproduction, a subliminal impression that short-term music peaks are handled without strain. But what about loudspeakers – can they deliver peak sound pressure levels the equivalent of those experienced when listening to high dynamic range music performed live?

The answer is generally no: most domestic loudspeakers, particularly direct-radiating designs, can achieve nowhere near the surprisingly high peak SPLs sometimes required to recreate the live experience.

And yet this fact is rarely commented upon and has even less frequently been the subject of measurement. When an amplifier is lab tested, you expect to see it assessed for maximum power output. But when did you last see the maximum output capability of a loudspeaker measured?

A key reason for this is that achieving high peak SPLs without resorting to horn loading is not easy, for reasons I will shortly describe. So the issue has been brushed under the carpet, often in the comforting assumption that listeners will not attempt to achieve realistic SPLs in the home. Undoubtedly this is often the case, and it's also true that a lot of recorded music – particularly modern recordings which have been mercilessly compressed to achieve higher loudness – does not require high peak SPL capability to be reproduced at high loudness levels. But it seems axiomatic that any sound reproduction system worthy of the label 'high fidelity' should be able to reproduce equivalent peak levels to those experienced when a listener is enjoying dynamically unconstrained music live.

At last there are signs that certain loudspeaker designers are taking this issue seriously. One of the headline capabilities of the



BeoLab 90 speaker [HFN Dec '16], for instance, is that it's capable of achieving 120dB SPL at 1m from 32Hz to 32kHz [see Fig 1], courtesy of its 18 drive units and 8.2kW of amplification per channel.

More pertinently, in that they promise to be far more affordable, it was revealed by PS Audio recently that it is developing a range of loudspeakers for which 120dB SPL peak output capability is also promised – a feature demanded by the late Arnie Nudell, creator of the mighty Infinity IRS, who until his death late last year was a key player in the PS Audio loudspeaker project.

Perhaps this is a flash in the pan after which loudspeaker design will settle back into its comfortable old ways of largely ignoring this issue. Or maybe, just maybe, we are on the cusp of a new phase in loudspeaker design's almost 100-year history.

## JUST HOW LOUD?

If we set as our task recreating the short-term peak SPLs of live music, just how loud do we need to go? Note that I am not talking here of average level, nor even of the peak levels you may read using an SPL meter (which in all probability seriously underestimates the true SPL peaks, which may only last for milliseconds). I'm referring here to instantaneous peak levels, a distinction you have always to bear

in mind when reading what research there has been into this issue, and even more so in what are frequently confused discussions online.

Not that there seems to have been a great deal of academic investigation of this subject. In fact much of the evidence is anecdotal. For instance, Dr Mead Killion, president of Etymotic Research and adjunct professor of audiology

**RIGHT:** Side view of a PS Audio prototype being designed for high output level capability. The company plans a range of loudspeakers capable of delivering 120dB peak SPL



at Northwestern University in the US, has written, '[I have] often measured the Chicago Symphony Orchestra at 104 to 106dB(C) in the last few bars of a selection (at the end of Stravinsky's *Rite Of Spring*, for example), corresponding to instantaneous (oscilloscope) peaks of 114-116dB.'

Individual instruments, listened to at shorter distances, can generate surprisingly high instantaneous levels too. I have recorded 113dB SPL from a mere triangle at 1m, using my calibrated speaker measurement microphone (which has a specified upper -3dB frequency of 100kHz and therefore takes into account ultrasonic as well as audible-spectrum frequency components).

### MISLEADING RESULTS

The most detailed study I've encountered of the peak SPLs generated by individual instruments and larger musical ensembles was published by Canadian audiologist Marshall Chasin in *Hearing Review* in 2006. Marshall Chasin has taken a particular interest in the protection of musicians' hearing, and in 'How Loud Is That Musical Instrument?' set about measuring just what peak levels musical instruments generate.

Table 1 [above, right] reproduces some of his results. In all cases the SPLs were measured at a distance of 3m from the individual instruments. The first column of figures shows the range of values observed with A-weighting applied to the measurement, which reduces bass and treble contributions. These figures serve as an example, when compared to the true peak levels of the last column, of how SPL measurement can give misleading results of instantaneous level.

In fact the under-reading of peak levels can be much worse than this if the meter characteristics are intended to give an indication of average loudness, like that of a VU meter (which has a risetime - to 99% of the final value - of 300ms ±30ms, rendering it useless as a detector of musical peaks which may last for mere milliseconds).

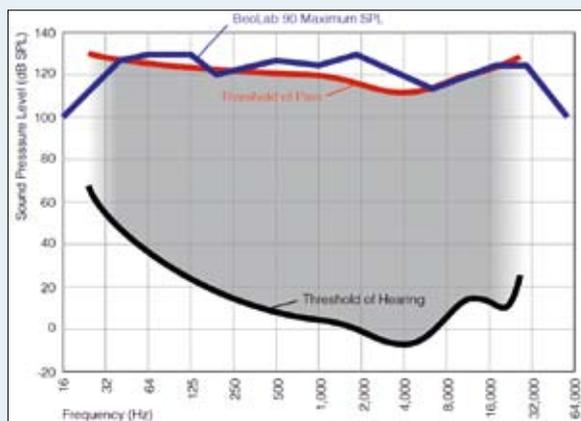
If Table 1 doesn't shock you then I politely suggest that it should. Chasin's results confirm that an output capability on short-term peaks of 120dB SPL is not an unreasonable ask of a loudspeaker

Instrument(s)	dBA	Peak SPL @ 3m (dB)
Loud Piano	70-105	110
Keyboards (electric)	60-110	118
Violin/Viola	80-90	104
Cello	80-104	112
Clarinet	68-82	112
Oboe	74-102	116
Saxophone	75-110	113
Flute	92-105	109
Piccolo	96-112	120
French horn	92-104	107
Trombone	90-106	109
Trumpet	88-108	113
Symphonic music	86-102	120-137
Amplified rock music	102-108	140+

**ABOVE: Peak SPLs generated by individual instruments and two ensembles (from M Chasin, *Hearing Review*, 13(3))**

**TOP RIGHT: The BeoLab 90 with its 18 drivers**

**BELOW: Fig 1 shows maximum output capability versus frequency for the BeoLab 90 at 1m (B&O data). The threshold of pain is sometimes considered to occur at higher SPL than depicted here**



truly worthy of the label 'high fidelity'. And ideally this should be achievable at a typical listening distance of 3m, say, rather than 1m. As we are about to see, that is a challenging specification.

We'd be getting ahead of ourselves to ask at this point: how can peak levels of this order be achieved? First,

to appreciate the measure of the task, we need to establish the order of peak levels that typical speakers of today can output. This is not, as I've explained, something that is routinely measured in reviews (even ours) and I've not seen any academic research on the topic either. Speaker manufacturers sometimes specify a maximum output capability but exactly how this is determined is not always clear. To get around



this scarcity of data, some years ago I wrote a software utility to explore loudspeaker maximum instantaneous output capability using simulation.

The software assumes closed box bass loading (it could easily be elaborated to cater for reflex loading) and requires the

specification of bass corner frequency, crossover frequencies and slopes, and three parameters for each drive unit: effective piston area, linear excursion capability

and maximum excursion capability. The first two driver parameters are usually quoted on driver spec sheets (as parameters  $S_d$  and  $X_{max}$ ).

If the third isn't specified then a value twice that of the linear excursion capability is a good guesstimate. With these figures specified, the software calculates the maximum excursion for each of the speaker's drive units when a specified WAV file is replayed with 0dBFS corresponding to a defined SPL at a defined listening distance.

Let's use this simulation software to determine how three loudspeaker designs behave when 0dBFS is set to 120dB SPL at 3m. The first speaker is a two-way with a 220mm bass driver and 29mm tweeter and has a second-order Butterworth crossover at 3kHz. The second is also a two-way, having the same drivers and crossover frequency but a ☺

*'If the results don't shock you I suggest that they should'*

4th-order Linkwitz-Riley crossover. The third loudspeaker also uses the same bass unit and tweeter but is a three-way design with a 120mm midrange driver operating between crossover frequencies of 400Hz and 3kHz, both crossovers being 4th-order Linkwitz-Riley.

In all three speakers the bass corner frequency is 50Hz. Effective piston area, linear excursion capability and maximum excursion capability are all typical for drivers of this size and type. (Specifically: 220cm<sup>2</sup>, ±5mm and ±10.5mm for the bass unit; 55cm<sup>2</sup>, ±1.0mm and ±2.0mm for the midrange; and 7.0cm<sup>2</sup>, ±0.2mm and ±1.6mm for the tweeter.) All the crossover slopes are acoustic, *ie*, electrical plus inherent driver roll-offs, and no account is taken of directivity.

**TEST TRACKS**

I chose three WAV files to process: my mono recording of energetically played triangle, Jennifer Warnes' 'Way Down Deep'

from *The Hunter* [Private Music 01005-82089-2], and an excerpt from John Cage's 'Cartridge Music' played by Jonathan Faralli [*Percussion*

XX, Arts DVD-A 47558-6]. The Warnes track is a stiff test of bass output capability, but there are worse; the Cage excerpt (running from 2m27s to 3m42s) contains some energetic percussion playing and has an unusually high crest factor (ratio of peak to RMS signal level) of 27dB on both channels.

All three speakers proved just able – only just – of reproducing the triangle at its measured peak SPL of 113dB SPL but couldn't manage much more (this at 3m listening distance). The limiting driver was the tweeter, but a surprising fraction of the bass driver's excursion was used up too, to the tune of 2.34mm at 113dB peak SPL. So all three loudspeakers were pushed to reproduce a single percussion instrument at a realistic level.

On more complex input signals they really struggled. To reproduce 'Way Down Deep' at 120dB peak SPL at 3m required excursions way beyond the linear ranges of both woofer and tweeter. The limiting

driver was the bass unit, which in all three speakers exceeded its linear excursion capability by 27.5/28.0dB (about 25x) for the left and right channels respectively. But the tweeter struggled too in the two-way with a second-order crossover, emphasising the benefit of higher-order high-pass slopes to protect tweeters. Peak tweeter excursion requirement dropped from 3.2/3.9mm to 0.41/0.62mm with the fourth-order crossover.

Peak linear output capability for all three speakers as complete systems was a paltry 92.0dB SPL at 3m, at which the average ITU loudness (Leq(RLB), both channels operating) was only 77.4dB SPL. And this, remember, is for a 50Hz bass corner frequency. Dropping it an octave to 25Hz reduced peak linear output capability to 88.2dB SPL and average ITU loudness to 73.7dB SPL.

The John Cage percussion excerpt proved even more challenging, with the bass driver again being

the limiting factor, although the tweeter was quite incapable of achieving 120dB SPL peak, by 12.1/15.9dB for the left/right channels even

with the fourth-order crossover. Peak linear output capability was 88.5dB SPL, and average ITU loudness – for what is energetic percussion playing – just 65.0dB SPL. Pathetic seems not too strong a description. The message is clear: if 120dB SPL peak

**RIGHT: The Infinity IRS with its 108 drivers in four columns is a classic example of a line source configuration. The speaker cost \$20,000 on its launch in 1980, the woofer towers coming with their own 2kW amps**



output capability is the target, we need more drive units. A lot more.

This requirement to use multiple drivers in each frequency band inevitably leads to the use of a line source configuration, the classic example of which is the mighty Infinity IRS, featuring 36 planar tweeters, 12 planar midrange drivers and six 300mm cone bass units per side. But line sources are no panacea – they introduce problems of their own.

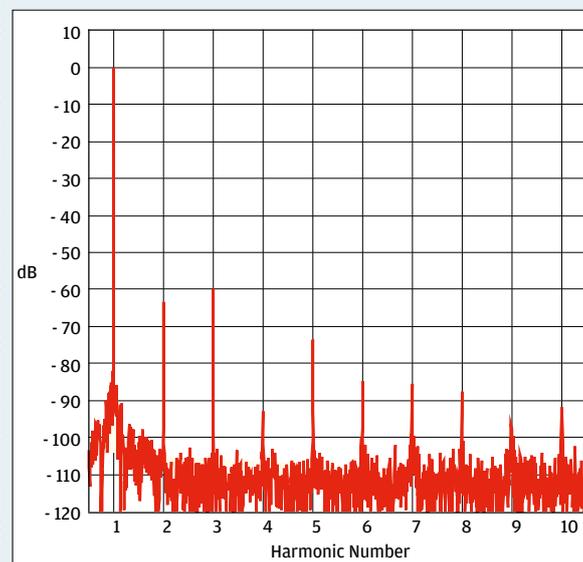
**LINE SOURCES**

A lot of tosh is written about line sources, particularly in praise of full-height lines which reach from floor to ceiling and – if the floor and ceiling are reflective, behaving as acoustic mirrors – approximate the behaviour of an infinite line source. What the careless proponents of full-height line sources fail to appreciate is that – because listening takes place in the nearfield – the frequency response at the listening position is not flat. Time delays from different sections of the line cause frequency dependent destructive interference resulting in a frequency response that declines from low frequencies to high frequencies at 3dB per octave (10dB per decade).

This can be equalised, potentially, but it means that the speaker input at 20kHz has to be 30dB higher than at 20Hz for the same acoustic output. In power terms 30dB is equivalent to a ratio of 1000:1, so 1kW input would be required at 20kHz to match the acoustic output from just 1W input at 20Hz.

Shorter line sources behave better in that the start of the 3dB ↪

**'Typical modern direct-radiating loudspeakers are failures'**



**BELOW: Graph shows distortion spectrum measured nearfield from the Magico S5 loudspeaker at 1kHz, 90dB SPL at 1m**

per octave roll-off is postponed to higher frequencies at practicable listening distances, but the frequency response now varies with distance from the line.

Fig 2 illustrates this for a 1m high continuous line source, showing the theoretical frequency responses at 1m (blue), 3m (red) and 5m (green) on the axis of the line centre. As well as these responses being distance-dependent, they have pronounced ripples around the 3dB per octave roll-off. The message is that it pays to keep line sources as short as possible, which in the context of achieving a given peak output capability suggests using as many drivers as necessary but no more.

Vertical line sources disposed side-by-side (*à la* IRS) also introduce off-axis response issues in the horizontal plane through crossover – another unwelcome consequence of this approach and an effect which the vertical disposition of drivers in most conventional speakers is specifically adopted to avoid.

**NATURE OF DISTORTION**

Thus far an implicit assumption has been that for achieving high SPLs it's sufficient to ensure that the drivers' linear excursion capability is never exceeded. But we need to look more closely at what 'linear' means in this context. To return to the amp analogy, we'd expect to see maximum output power quoted with distortion as a parameter, typically 1% THD. What distortion level is used to define a drive unit's linear excursion capability? The perhaps shocking answer is that it's usually not 1%, or even 3%, but 10%, which makes the use of the term 'linear' somewhat disingenuous.

To be fair, it's anything but well researched just how much nonlinear distortion, of what character, we can tolerate at high SPLs, where our ears themselves introduce significant levels of distortion. Still, few of us would consider 10% distortion as high fidelity. And the nature of the distortion is as significant as its overall level.

It is often supposed, and at times actually stated, that loudspeakers – unlike amplifiers – are not prone to

introducing high-order nonlinearities so that, perceptually, loudspeaker distortion is relatively benign. But measurements of drive unit harmonic distortion belie this claim.

As an example, take a look at the graph showing the 1kHz distortion spectrum measured from the Magico S5 [see p29] in the course of preparing the lab report for its review [HFN Dec '12]. This is not chosen as a bad example; in fact the S5's 1kHz distortion performance is quite typical of a modern loudspeaker. Low-order harmonics predominate but if we apply  $N^2/4$  weighting to each harmonic – which better reflects the amount of intermodulation distortion that will be introduced with a complex signal – the total distortion more than doubles from 0.125% to 0.298%.

This is at 90dB SPL at 1m (81.5dB at 3m). At higher SPLs we can expect the higher-order harmonics to increase in level faster than the lower-order ones. Assuming a simplistic distortion model, the relative level of the second harmonic will increase in proportion to the signal level, the third harmonic in proportion to the square of the signal level, etc.

Fig 3a shows an example of actual harmonic amplitude behaviour, for the first seven

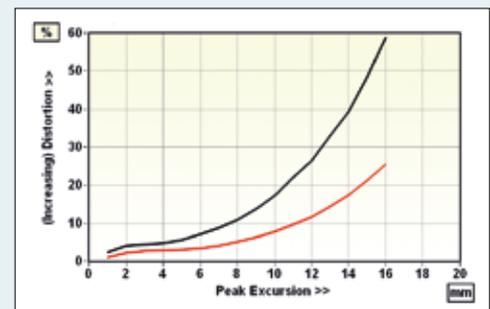
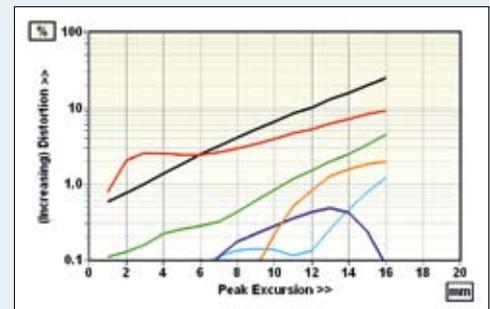
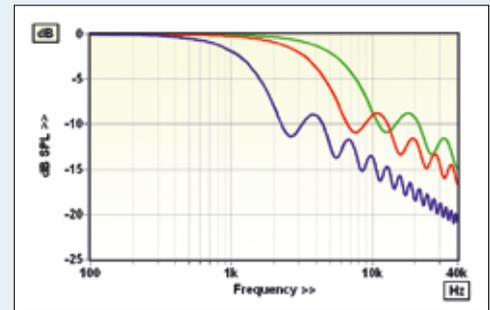
harmonics, of a 12in subwoofer driver in free air. Linear excursion capability for this driver is specified as  $\pm 13\text{mm}$ ; THD (Fig 3b) at this excursion is 14.4%,

the  $N^2/4$ -weighted figure 32.9%. (This measurement was made using a micro-epsilon ILD1700-50 laser displacement sensor to determine cone excursion, with the acoustic output captured by a GRAS 40BE measurement mic. Mic distortion is negligible, even when performing a nearfield distortion measurement as here, as the 40BE's specified input capability is 166dB SPL for 3% THD.)

**MUCH TO LEARN**

I hope that this article has gone some way to persuading you that typical modern direct-radiating loudspeakers are abject failures when it comes to mimicking the instantaneous sound pressure levels

'The use of the term "linear" is somewhat disingenuous'



**ABOVE: Fig 2 (top) shows theoretical frequency responses for a 1m high continuous line source at 1m (blue), 3m (red) and 5m (green).**

**Fig 3a (middle) shows distortion versus peak cone excursion for a 12in subwoofer driver in free air (2nd harmonic, red; 3rd, black; 4th, orange; 5th, green; 6th, blue; 7th, cyan).**

**Fig 3b (bottom) shows THD (red trace) and  $N^2/4$ -weighted THD (black trace)**

generated by (certain) musical instruments, let alone instrumental ensembles. But there is much yet to learn. In particular we need to know what distortion is acceptable (*ie*, imperceptible) at high SPLs, in order to gauge exactly how many drivers are necessary in each frequency range. And that calculation would be further assisted by having solid statistics on the inherent excursion requirements across a wide range of music recordings.

Most of all, we have yet to experience and understand just how much improvement there is to the realism of loudspeaker reproduction when the speakers are capable of generating instantaneous SPLs at the listening position of around 120dB – with, critically, sufficiently low distortion to deliver such elevated levels cleanly. We may find that the ability to achieve this endows direct-radiating speakers with some of the qualities long cherished by horn enthusiasts – only without that pervasive horn coloration. ☺