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General Review

Speech and music is noise with meaning. The recording and reproduction of sound is imperfect, and the imperfections in these processes reduce meaning and add noise. The art of the loudspeaker designer is the employment of science to help increase meaning for reproduced sound. An understanding and familiarity with music and live sound is fundamental for a reasoned application of acoustical engineering to the still-imperfect process of loudspeaker design. Great advances have been made with materials technology, refined acoustical modeling, electrical theory and design software, all these helping to manipulate, control and balance all the factors involved in the engineering and construction, but there remains a substantial human component, namely the subjective judgment of reproduced sound quality, which is a skill the loudspeaker designer must acquire.

Some design engineers may view speakers as acoustical machinery, and thus design and build them as such. Conversely, loudspeakers must be considered as imperfect reproducers of speech and music. If you know and love music, then the machinery design part of loudspeakers should be guided by a continual assessment of the quality of the musical experiences that they create. Here science must serve art.

Reference ‘monitor’ speakers may be designed which are highly competent mechanically and acoustically, are usefully informative, but which may not fully inspire the listener with the quality of their musical performances. Highly qualified and trained engineers may well be responsible for numerous notionally accurate loudspeakers while some engineers are not particularly musical. Often they imagine that application of pure science, ‘done by the book’, will be sufficient to complete the work.

1.1 Early Loudspeakers

It is some 90 years since the ubiquitous moving-coil loudspeaker was first developed as we know it, the mass-controlled, paper cone direct radiator: an electrodynamic transducer which converts electrical current into sound pressure at a useful loudness. In contrast to most other sound transducers it possesses an intrinsically uniform frequency response. It is clearly highly reliable in use, and comes with the proven potential for economic manufacture.

Before this development there were numerous ‘earphone’ type transducers, moving iron and the like of various kinds for music reproduction, some ‘amplified’ by improved coupling to the air with various early horn configurations. Certainly, somewhat earlier,
primitive forms of moving coil and diaphragm sound signal reproducers had been made. Back in 1874, a U.S. patent for Siemens by Ernst Werner, was one of these, though at that time no electrical audio signals were available to drive it and so it was never heard to reproduce sound, instead emitting pulsed signal noises. And certainly, Peter L Jensen working with Pridham, (Figure 1.1) had developed a significantly powerful horn loaded loudspeaker by 1914, where the transducer employed a 75 mm diameter diaphragm of nickel silver alloy and employed electromagnetic field excitation acting on the moving coil. It was used successfully for large-scale public addresses for many years.

However, the familiar mass-controlled direct radiator moving-coil cone loudspeaker, whose principle is so effective that its key elements have remained essentially unchanged to this day, came with ‘the New Hornless Loudspeaker’ of 1925 by Rice and Kellogg of GE (USA). This set the stage for the, low-resonant frequency, direct radiating type of drive unit we know so well, a driver where a good part of the primary frequency response is intrinsically uniform with frequency, and which also may be acoustically loaded at lower frequencies to usefully extend the working range, by controlling the potential for front (positive) to back (negative) radiation cancellation from this intrinsically dipolar transducer.

### 1.1.1 The Elements of the Ubiquitous Cone Loudspeaker

To build such a transducer, take an affordable magnet and incorporate a simple arrangement of magnetically permeable ‘soft’ iron to help concentrate much of the available magnetic flux into a narrow radial gap using a cylindrical, central magnetic pole. A small light coil, a ‘solenoid’, is wound on a low mass former. This can be a tube of thin card. The assembly is suspended freely in the magnetic gap using a radially corrugated flexible disc or similar, allowing axial motion of a quarter centimeter or so.
In accordance with Maxwell’s electromagnetic equations, an axial force is generated on the coil when current flows through it. This force is the product of $B$, the magnetic field strength, $l$ the length of the wire immersed in that flux field and $I$, the current flowing through the coil. This force coupled relationship is fundamentally linear and consequently there is very little inherent distortion.

It is intrinsic for a moving-coil motor that there is effectively no lower resolution limit for small signals. An infinitely small electrical input will produce an equivalent and essentially infinitely small sound output. Another excellent feature of the moving-coil transducer, generally taken for granted, is that despite its nature as a moving mechanical device, it is essentially noiseless. It does not grate, scrape or whirr. Apply a sub-audible 5 Hz sine-wave current and you can see the coil move, but silently. The moving coil used on its own generates almost zero sound output. Radiated sound level is proportional to the area of air load driven or coupled by the transducer element, and for the coil alone, it comprises a thin ring of negligible radiating area.

It is essential to couple this moving element to a larger air load and thus a rigid, light diaphragm, generally of much larger area, is securely bonded to the coil former. Typically, such larger diaphragms have their own flexible outer surround, constituting a second suspension, fixed to an, skeletal, non-reflective support frame or chassis, the assembly providing the vitally important axial centering of the moving system, which can now be positioned in a close tolerance magnet gap. Such fine tolerance helps increase the magnetic flux density in the gap so maximizing efficiency and thus loudness.

We know that flat paper sheet is desirably lightweight, but it is very weak in bending. However, paper is remarkably stiff in tension. To make use of the latter property simply cut out some suitable paper in a useful shape, curl it up into a cone and glue the remaining seam. This simple conical structure exhibits an extraordinary axial stiffness for its mass, a marvellous means of coupling a much larger area of air load to that otherwise near silent moving-coil motor, so aiding conversion efficiency of force into sound. The coil former is firmly glued to the cone apex.

Here acting as an acoustical transformer, the cone or diaphragm matches the much lower acoustical impedance of the air load to the higher driving force impedance of the coil assembly, thus greatly improving the efficiency of energy transfer from electrical power, now providing readily audible sound pressure.

This signal path includes the translation of electric audio currents to mechanical forces; these are then coupled to a cone to usefully radiate sound pressure to be heard at a distance. The result is the familiar loudspeaker. This elegant principle has proved highly useful and effective for almost a century, even if in absolute terms the conversion efficiency from input electrical watts to acoustic watts is quite low, typically less than 1%. Fortunately, amplifier watts are easy to come by and our hearing is exquisitely sensitive; in practice one acoustic watt goes a very long way.

Include the virtue of very moderate cost, and noting that general purpose loudspeaker drivers may be mass produced like light bulbs, and it is these fundamental strengths that make the moving-coil principle so very effective, and so very popular. Over 99% of all the loudspeakers ever made have been moving-coil direct radiators. And the operating principle may be used over a very wide range of applications, from low-power speech reproducers of just 2.5 octaves bandwidth and a modest 75 dB maximum sound pressure output, built on a frame just 20mm, to low-frequency capable monsters of
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600 mm, capable of generating 20 Hz sound waves at body shattering 110 dB pressure levels, still more if acoustically loaded by a horn and/or aided by a local boundary.

Humans have sensitive hearing and even a low-efficiency drive unit, at typically 0.5% for the conversion of electrical to acoustic power, may be more than loud enough for many purposes. Indeed, the vast majority of domestic direct radiating speakers, including hi fi designs, are of similarly low efficiency. An electrical watt converted to sound level by this means will result in an average of 86 dB spl at 1 m, or about 80 dB in-room for a stereo pair; and in practice this is satisfactorily loud. For comparison, normal speech at 2 meters is about 70 to 73 dBA while shouting might raise 80 dB. Orchestral crescendos might raise 100 dB in room.

1.1.2 Loudspeaker Types and Technologies

Most moving-coil cone loudspeaker drivers manufactured are ‘full range’, nominally covering 150 Hz to 7 kHz, −6 dB, and when provided with a housing or enclosure of some kind are quite satisfactory for general purpose reproduction of speech and music. Where higher standards are required, for example, greater loudness, wider frequency response say 30 Hz to 15 kHz, and with a more consistent off axis directivity, the frequency range is usually subdivided, to be shared amongst different sizes of drivers each suited to specific narrower ranges, such an arrangement forming a speaker system. Specialized smaller drivers intended for higher frequencies, smaller so that the sound radiation angle remains suitably wide, may typically employ a light dome, which may be concave or convex, formed from a variety of materials such as paper, moulded plastic foil, resin doped fabric, metal foil such as aluminium or beryllium, or even vacuum-deposited pure diamond. These elements fitted as a cap to a voice coil former. In sizes down to 19 mm effective radiating diameter, and with the use of high technology stiff low mass materials, the frequency range may in some cases extend to well beyond 40 kHz. Such performance helps to ensure good results up to the nominal industry agreed steady state perception limit of 15 to 20 kHz.

More recent work on perception suggests discrimination of leading edge transients with a bandwidth extending to 80 kHz, and this constitutes a subtle sound quality issue. The perception of fast rise times[1–3] persists even for older listeners and is not related directly to the well-known hearing sensitivity limits applying for steady-state tones. Designing for a greater than nominal 20 kHz bandwidth is worthwhile where the budget permits, and in any case often results in superior subjective performance in the accepted steady state perception range.

1.2 Audible Frequency Range and Wavelength

By apportioning the accepted audible frequency range to appropriately sized combinations of drivers, these mounted in a suitable baffle or an enclosure, moving-coil technology can cover a frequency range of 20 Hz to 80 kHz, mathematically a massive ratio of 4000:1. Note that this great span corresponds to radiated acoustic wavelengths extending from 17 metres in the bass to just 4.25 mm in the high treble. Physicists and materials scientists may well sound warnings in respect of such a wide frequency range, highlighting the potential engineering difficulties which may be incurred, for example, where the
radiation efficiency over frequency is dominated by driver size. The mechanical properties of materials used, their stiffness and damping, will vary considerably over such a wide range. The loudspeaker designer needs to keep this warning concerning materials science in view, seriously consider the properties of materials over frequency and temperature, and try not to attempt the impossible.

With some difficulty and considerable expense loudspeaker systems with that 4000:1 frequency range have been designed for costly high-fidelity installations. Typically, this near 11 octave span may be reached with a set of four moving-coil drivers, each of appropriate size, scaled for their respective frequency coverage.

The most ambitious of these 'hi fi', high fidelity loudspeaker examples can cost as much as a high-performance car, and with still greater sales markup, and yet the humblest moving-coil drive unit, for example, intended for speech and portable radio application at moderate loudness, may be priced in as little as tens of cents in typical, industrial high-volume quantities.

1.2.1 Horn Loading and Efficiency

When the diaphragm of a moving-coil driver is loaded by a horn, this coupling a larger area of air load to the diaphragm, the improved acoustical matching will substantially increase the efficiency. This is vitally important for addressing larger audiences at greater sound levels. It is possible to reach a conversion efficiency of almost 50% over narrower frequency ranges with this technique, compared with the typical 1% efficiency for the usual larger size of direct radiating high-fidelity speaker. With typical horn designs, a fairly easily obtained 40 electrical watts can deliver a seriously intense, very loud, 15 acoustic watts, sufficient to cover very large audiences at realistic volume levels.

Horns are inherently directional, considered a disadvantage in some cases for domestic use and nearfield studio monitoring, but conversely, they offer the powerful benefit of beaming the sound more selectively to where it is required.

Judged subjectively, domestic listeners also report that perceived musical dynamics are improved for all loudspeakers in proportion to higher effective efficiency, here noting that higher efficiency is a natural attribute of horn loading. Despite potentially greater coloration and a narrower spread of energy into the local acoustic, a greater dynamic headroom is conferred, and the need for less powerful amplifiers are important benefits.

1.2.2 Moving-Coil Longevity and Advantages

Moving-coil drivers have proved to be remarkably durable with many examples still operating after rather more than half a century of use. We can observe that numerous alternative sound reproducing technologies have been proposed and tried out, such as magnetically driven ribbons, shape changing piezos, electrostatic membrane drive, ionic plasma sources, and ultrasonic demodulation in air. Some of these principles remain in use, if on a small scale. However, like the wheel, the moving-coil principle remains ubiquitous. And for no better reason that it is economical, durable and effective (see Figure 1.2).

At times, it may seem that some new transducer and/or acoustic loading innovation appears in the specialist loudspeaker field, with many of these claimed by their inventors
and supporters to supplant the substantially pistonic moving-coil driver with its generally simple box enclosure. However, no alternative technology has so far emerged to mount a credible value challenge and the moving-coil principle remains pre-eminent in terms of effectiveness, economy, wide application, flexibility, and performance potential.

While this introductory review concentrates on the moving-coil principle applied to loudspeakers, this simple mechanism is also widely used in precision actuators, both for the high-speed focus and the high-resolution tracking mechanisms for laser optical heads used for video data and compact discs. It is also applied in the most popular form of microphone and not least, for almost all high-fidelity headphones and earpieces, as well many applications in related communications apparatus.

1.2.3 Loudspeaker Design Is Not an Exact Science

Over the last 50 years the growth and worldwide acceptance of the high-fidelity market, and the manifestly high sound quality standards achieved in recording and broadcast studios, have given great impetus to high-performance loudspeaker design. Nevertheless, the loudspeaker remains the most argued-over device in the entire high-fidelity chain; every aspect of its design and execution has been subject to lengthy and involved discussion, even dispute. Although audio engineers like to deal in facts, much to their dismay, fashion plays a considerable part in the burgeoning consumer market and loudspeakers are not exempt. A designer building to a high standard for bandwidth, linearity, and maximum loudness will likely deliver quite a large object, very probably a floor standing enclosure of 50 to 150 litres enclosure volume. In view of the likely high price, the market demands that elements of design style and finish are to a high standard, commensurate with luxury furniture and related fashion sectors, commonly automotive. While a car may well be designed to a high performance standard technically, it is now expected that an excellent appearance will also be commensurate with the price.
Likewise, designers of high-quality speaker systems need to include substantial industrial design input at an early stage, and must carefully consider all elements including colour and finish, for example, piano gloss lacquer and custom veneers and colours. Customers now expect that contemporary luxury standards are met in all aspects of design, build, style and finish.

1.2.4 Passing Technologies and Fashions

Concerning less commonly encountered technologies and design approaches, occasionally a design which would otherwise be considered technically ‘unbalanced,’ a loudspeaker which a consensus of trained electroacoustic design engineers would consider includes an obvious design weakness or error, will nevertheless find public and even specialist consumer journal review approval. In some cases, such a model may be claimed to have a ‘new and better sound,’ perhaps deriving from an alternative bass loading principle, or a new transducer technology, or a reworked sound dispersion method. Unfortunately, for many such products other important aspects of performance may well have been neglected by the designers in their perhaps blinkered efforts to exploit that ‘special’ feature and resulting novel sound. After a cooling-off period, the market generally regains its senses and a longer-term consensus concerning reliable opinion for natural sound reproduction obtains.

1.2.5 An Emerging Consensus for Performance

Audio professionals are inevitably conditioned by experience and may be suspicious of any change, even for the better. Sound quality judgments which are free of prejudice, made by those who have frequent contact with musicians and live programme sources are more reliable than most. Nevertheless, there has been an encouraging development over recent years, in that a degree of rationalisation for performance standards has occurred, on both the domestic and professional fronts. Audio researchers and designers are beginning to agree on a common standard based on factors such as a natural sounding frequency balance, good uniformity of acoustic output, both on and off axis, together with lower distortion and lowered colouration. This common ground has developed despite dissimilarities of design approach and philosophy. It suggests that a consensus is developing concerning gathered data, objective and subjective, and informal opinion concerning speaker performance and quality. Such a situation presents a dramatic reversal of the state of affairs which prevailed in the 1960s when hi fi was beginning to take off.

Then there was a marked divergence of opinion over subjective sound quality, especially from loudspeakers. Indeed, this was so extreme that the line of products from the major manufacturers could be readily identified by a specific ‘in-house’ sound that pervaded all their designs. In addition, a country or even a region could well be involved, for example, for the United States, ‘West Coast’ or ‘East Coast’ frequency balances. At this period, a typical domestic ‘hi fi’ speaker system comprised a 250 or 300 mm chassis diameter bass-mid unit, with a light paper cone of fairly high resonance frequency, driven by a 33 or 50 mm diameter voice coil wound on a paper former. A separate 75 or 100 mm paper-cone tweeter covered the treble range and was often concentrically mounted on the bass unit frame. The drivers were mounted on the inside
face of the front panel forming a frontal cavity, the enclosure was likely to have a typical volume of between 60 and 120 litres, and generally employed reflex, that is, vented, low frequency loading. Performances, both for distortion and for colouration, for example, from unnatural ‘ringing’ effects due to in-band resonances, and for tonal balance or a ‘natural timbre’, generally fell well short of the performance of even low-cost models today. Measured frequency responses frequently resembled a series of jagged crags accompanied by obvious and obtrusive audible colorations (Figure 1.3).

It is fascinating to consider the ‘ideal performance’ that a contemporary speaker designer aimed at achieving in those times. (Table 1.1), even though those typical ‘hi fi’ speakers then on sale, as noted above, fell rather short of this objective. This target specification was inherently limited by the level of achievement typically attained by the industry for the time (Table 1.2 and Figure 1.1). The target efficiency/sensitivity was set at 100 dB SPL for a 1 W input at 1 m relative to a typical commercial system of the day, typically 94 dB/W. Presumably this high value reflected the relatively low power output of contemporary hi fi amplifiers where 10 to 20 W/channel maximum for an 8 ohm load, was commonplace while many failed on 4 ohms loading.

Interestingly only mild improvements in response flatness or bandwidth were thought possible due to an acceptance that inherent diaphragm resonances were largely incurable. Commercial speakers of the time typically provided a noted 35 Hz ‘useable’ limit at a substantial 16 dB down, despite their significant size, and a 15 kHz limit frequency typically some 12 dB down, which contrasts with the somewhat more ambitious −10 dB limits which were then suggested for an idealised system. Note that the +, −5 dB

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**Figure 1.3** Axial response of a typical early 1960s loudspeaker system.

**Table 1.1** Idealized loudspeaker system specification, circa 1960.

<table>
<thead>
<tr>
<th>Efficiency (sensitivity)</th>
<th>100 dB at 1 m for 1 W at 1 kHz (8 ohms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency response</td>
<td>100–10,000 Hz, ±6 dB;</td>
</tr>
<tr>
<td>Response limits</td>
<td>35 Hz at −10 dB; 15 kHz at −10 dB</td>
</tr>
<tr>
<td>Polar response</td>
<td>100–10,000 Hz: better than 6 dB down at a 60° arc limit</td>
</tr>
<tr>
<td>Distortion</td>
<td>Less than 10% at 35 Hz, sound level unspecified (likely 1 W input)</td>
</tr>
<tr>
<td>Distortion</td>
<td>Less than 2% above 100 Hz (likely 1 W input)</td>
</tr>
<tr>
<td>Cabinet volume</td>
<td>60 litres internal</td>
</tr>
</tbody>
</table>
amplitude limits which were aimed for, also show relatively little ambition compared with those finer limits now attained with more recent practice.

It should be noted that specifying for such a wide tolerance for amplitude not only allows for significant variation in timbre, tonal balance, from sample to sample but also obscures the important question of pair matching. Closer tolerances for amplitude versus frequency are now understood to be vital to greater sample-to-sample consistency and thus genuinely higher performance. Closer tolerances are also key to superior stereo image performance, where the quality of virtual image sharpness is now known to be strongly dependant on the accuracy of loudspeaker pair matching.

### 1.2.6 Those Electroacoustic Fundamentals Were in Place

While the performance data of such historic commercial practice looks disappointing now, it is perhaps surprising to note that the basic technology and theory now considered essential to present-day higher-quality loudspeaker design was already well known to advanced specialists in the field. Furthermore, such research was well documented in many papers, periodicals and books. Commercial speaker designers were aware of colouration effects which could often be associated with errors in frequency response, and with the connected so called delayed resonances in cones and structures; designers appear to have done little about them, despite the excellent research at the BBC by Shorter that had been conducted almost 20 years earlier concerning audio band resonances, their sources and effects. While extant in the reference literature, many of the now accepted loudspeaker technologies and principles were rarely applied commercially, and the overall approach to design seemed to be a rather haphazard, even amateur exercise. Many loudspeaker companies were small scale, almost garage operations. Perhaps it was felt at the time that there were so many acoustical problems acting in concert that solving just one or two of them would not result in a significant improvement in sound quality. And it may be argued that several hi fi speaker designs remain rather amateur, even now.

However, some companies were researching highly advanced technologies, and were also working on more sophisticated designs. Some made it into production, albeit in limited quantities. Hugh Brittain, researching in the 1950s at the GEC Hirst Research Centre at Wembley, designed a 200 mm ‘BCS1851’ aluminum cone, full range driver,
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loaded by proprietary ‘Periphonic’ enclosures. Ted Jordan worked with Brittain, and later and went on to develop a whole range of advanced moving-coil drivers and systems when he moved on to Goodmans Loudspeakers, then located close by in North London. Then, in the mid-1960s Jordan founded Jordan-Watts, of ‘JW Module’ fame. The JW module was a highly advanced, futuristic, unit full-range driver which used a single flared aluminum cone, 100mm dia see 7.6.1. The assembly was built into a die-cast, acoustically porous, box-like frame. The lead out wires were configured as an integral tangential voice coil suspension, made of beryllium copper bars, and the module was designed with integral low-frequency damping making it largely uncritical of alignment and enclosure volume.

By 1967, K.E.F. Electronics (UK) had released the Carlton, designed largely by company founder Raymond Cooke, this a costly three-way, closed box, considered well ahead of its time, and fitted with a substantial planar rectangular composite diaphragm bass driver, a polystyrene foam core with reinforcing skins, called the B1814, measuring unsurprisingly, 18 by 14 inches. The diaphragm skins were aluminium foil. The system also incorporated a highly developed mid-band transducer. This, the M65, covered a 250Hz to 4kHz range and employed a 65 mm hemispherical dome formed of a rigid polyester polymer, fitted with an advanced double suspension to control rocking. It was back loaded via the hollow pole piece by an extended transmission line pipe, some 0.8 m long. This was filled with graded density long-fibre wool for effective back wave absorption and predates the present graded lines used by B&W by some 35 years. The use of an aluminum voice-coil former provided a high-power handling capacity (Figure 1.4). Finally, high frequencies were covered by the T27, here with a 19 mm polyester laminate dome, typically operating to 30kHz; the latter design was so advanced that it continued in production for almost 30 years and was also chosen for the BBC LS 3/5a studio monitor.

At that time, very few mid-range dome drivers were available, the other well-established example being that employed in the classic American design, the, AR-3, designed by co-founder of Acoustic Research (AR), designer Edgar Villchur, was setting

![Figure 1.4 KEF mid-range dome loudspeaker with absorbent line loading.](image-url)
standards for extended, uniform bass from a compact sealed-box (IB) enclosure, if at necessarily low efficiency. Low impedance and low sensitivity also characterised these models. AR also introduced one of the first types of wide directivity rigid ‘dome’ type units for mid and for treble, these 2-inch and 3/8-inch sizes first disclosed in 1958.

Villchur is now acknowledged as the leading commercial exponent of the volume compliance dominant sealed box with his original and highly successful AR-1 ‘acoustic suspension’ speaker. This was a radical commercial development when developed in late 1953, with a patent granted in 1956 (but later revoked), when most loudspeakers were much larger in volume and with generally rather less low-frequency extension and certainly much less uniform frequency responses. A two-way design of 40 litres, by today's standards the original AR-1 employed an improbably large 8-inch mid-treble unit, combined with a 12-inch long throw, very low resonance bass driver, the alignment dominated by the enclosure air volume stiffness. Efficiency was low while its dynamic range was limited by the relatively small amplifiers of the time. In the late 1950s in the UK a contemporary Goodmans ‘Audiom’ driver had a similarly low free air bass driver resonance at 16 Hz, and was designed for a three cubic foot box for a 50 Hz in-cabinet resonance. Incidentally Peter Walker, founder of Quad, noted that there were sales of a UK designed ‘acoustic suspension’ loudspeaker in about 1937, coincidentally called the ‘Audiom 8’ and significantly predating the Villchur development.

Back in 1967, Bill Hecht patented a 2-inch soft fabric dome tweeter in the United States, (here with an unusual form of internal suspension), while complaining at the time that the raw fabric diaphragm disappointingly would operate to only a few kHz due to lack of rigidity. But the later addition of a rubberised doping had a surprising effect, resulting in a smooth response to over 12 kHz. Thanks to hysteresis from the doped fabric, this exhibited fortuitous and substantial stiffening with increasing frequency, combined with useful damping.

Boston Acoustics used the Hecht design in large quantities while Philips independently produced a 1-inch doped soft fabric dome in Europe with an integral edge suspension, which was also very widely used and endlessly copied. This development essentially spelled the end for the then ubiquitous cone tweeter with its difficulties of irregularities in frequency response, consistency and directivity, though some designers regretted this transition, hearing some deficiencies in terms of clarity and dynamic expression with many of the soft dome transducer designs.

One non-moving-coil loudspeaker system surviving the passage of time is the Quad ‘57’ full-range electrostatic loudspeaker designed by Peter Walker and DTN Williamson, production dating from 1957 and still well regarded for its exceptional naturalness (to which I can testify), and obtainable on the second user market. While it was by no means the first electrostatic speaker, with other examples dating back at least 80 years, its push-pull, constant charge design helped give unprecedentedly low distortion and conferred great subjective transparency. (The underlying low distortion, constant-charge principle had been previously proposed and fully analysed by Hunt.) Accepting that moderate power handling and a low voltage sensitivity are specific limitations, its subjective performance in terms of low distortion, neutral timbre, very low coloration and excellent transient accuracy continues to bear favourable comparison with many current loudspeaker designs. The reputation of its successor, the ESL63, whose original design dates from 1963, has also survived; and it is still in production, (now with a revised model number), but remains largely unchanged. Standards are still set here in
several respects by this near zero moving mass technology. Here the large area, low excursion film diaphragm is just one tenth the thickness of the human hair.

1.3 The BBC Contribution

By the mid-1960s, proprietary BBC engineering research for a new generation of monitoring loudspeakers was under way, largely prompted by the considerable inconsistency experienced both with commercial drive units and with complete bought-in commercial systems which had been chosen for programme quality monitoring work. These new BBC designs incorporated cones of a vacuum formed synthetic co-polymer (Bextrene) of more consistent performance rather than the usual paper/pulp formulations and this progress, inspired by Shorter’s research, was now well advanced, extensively developed and prototyped by a team primarily led by Dudley Harwood and including electroacoustic engineer Spencer Hughes. This project proved to be of great significance as it was clear that a major improvement in both loudspeaker quality and consistency had been achieved during this development period.

The high standards set by these designs, with their well damped, critically shaped polymer cone drivers, in particular the LS5/5 three-way with a 200 mm mid unit, acted as a great stimulus to the UK hi fi industry. Through attempts to attain this standard at a commercial level numerous new developments and designs appeared, many of these rather more closely related to the BBC originals and some less so. Raymond Cooke, founder of KEF also provided valuable production experience in respect of these new technologies and KEF manufactured a number of BBC monitors both under contract and under license for retail sale.

1.3.1 A Step Change for Reduced Colouration and Improved Response Accuracy

Independently, and also designed for commercial sale, ex BBC engineer Spencer Hughes developed a compact two-way system (BC1) derived from the LS5/5 technology, this for his own new company Spendor, and using his own proprietary highly developed bass-mid driver. This derivative proposal for a compact two-way system had initially been rejected by the BBC.

The consumer loudspeaker market in the late sixties was quite conservative. At that time, the favourably reviewed high quality systems were relatively large (60–150 litres), and when this new 40 litre contender, the BC1, of compact dimensions became available it was initially viewed with considerable suspicion. This radical design employed a 200 mm cast alloy chassis, Alnico magnet bass-mid driver, fitted with a Hughes developed Bextrene co-polymer bass-mid diaphragm of critical flare, vibro-elastically damped with a hand-applied coating of an aqueous polyvinyl acetate based mix, terminated by a custom surround termination in white PVC, and which driver at least in part, clearly benefited from the prior BBC research. The HF unit was a carefully selected, BBC-approved Celestion HF1300 using a 34-mm acoustically loaded rigid diaphragm.

The result, the BC1 compact loudspeaker sounded quite different from the relatively massive and more costly systems available and, in fact was judged rather closer to the sound of live sources than most of its larger and more costly contemporaries, and
indeed rather close to the highly rated Quad electrostatic. After some acclimatisation some listeners also became aware that the initially perplexing difference between its sound and that expected from regular speakers was in fact due to its rather closer approach to realism, particularly for spectral balance, pair matching, clarity on transients and most especially low coloration, the latter achieved through advanced control of decay resonances. This compact speaker represented a skilled balance of the important parameters responsible for natural sound quality, and yet it took almost a decade for this level of performance to become fully appreciated by the wider industry.

Further, when the BBC had occasion to audition this small Spendor they chose to employ it after all, directing Hughes to complete a transformer matched version under BBC auspices, designating it LS3/6a, and which production was then licensed to Rogers. While a few dozen of the official LS3/6a were manufactured, some 2,000 of the more commercially orientated BC1 were supplied to the professional market, including many to the BBC. The BC1 continued in very successful production for many years, reaching 20,000 pairs, and it was later subject to development to improve the power handling, cognisant of rapidly emerging rock music programme demanding more low frequency power. This change aided growing domestic market sales, though the Rogers-built version held to the official BBC licensed specification.

By 1977, Spencer’s former chief Dudley Harwood had left the BBC engineering department to establish Harbeth, and also launched another LS 3/6 sized design, but here with a 25 mm soft-dome tweeter, and a new design of bass driver fitted with a proprietary, self-damped, co-polymer polypropylene cone. This polymer Harwood had jointly patented for loudspeaker application with David Stebbings (BBC) and Joseph Pao (the latter pair going on to found Chartwell, here also to exploit this diaphragm technology). Chartwell also went on to build BBC licensed designs.

Many UK speaker designs which followed gained much from the BBC sound quality improvements and consequently showed much reduced coloration and greater consistency. Subsequent and varied polypropylene cone formulations are now used in millions of driver diaphragms around the world.

1.4 Emerging Standards

The performance of today’s typical high-quality domestic systems would have been disbelieved in 1960, for they exceed the majority of requirements of that contemporary ideal specification by a handsome margin. The particular model described in the following table is for a compact, so called ‘bookshelf’ bass reflex design, now widely popular, and intended for free space mounting on a 46 cm high stand, employing a moulded 160 mm diameter polymer-coned bass–mid-range unit working in conjunction with a 25 mm diameter soft-fabric dome tweeter. However, note that for this system (Figure 1.5), the sensitivity/efficiency is a massive 12 dB lower than that 1960s target ideal. This is the inevitable compromise resulting from the requirement for extended bass response from domestically acceptable compact enclosures. Fortunately, over the intervening period much larger and comparatively inexpensive 50 to 150 W amplifiers have become commonplace for matching this low efficiency (Table 1.3).

Such low efficiency and sensitivity is the inevitable outcome of the fashionable requirement for wide bandwidth from increasingly compact enclosures, also, to some
degree, the drive for substantially lower colouration with better control of delayed resonances. This often involves increased diaphragm mass. The tighter tolerance seen for the amplitude response is also important. Together these also qualify a significantly wider frequency response, also serving to illustrate a considerable manufacturing improvement achieved in the uniformity and consistency of sound output with frequency. The standards achieved for distortion and polar, off axis response are also substantially improved, as is the higher power rating of 100 W programme which is 6 dB greater than the typical equivalent for 1965. This is inevitably necessitated by the reduced efficiency of the system as well as the need to cope with considerably higher power output of modern amplifiers, up from the previous 15 W to typically 75 W now. We note that there a few of the larger domestic amplifiers are now capable of 2,000 W/channel into 4-ohm loads. One consequence of a high-power requirement arising from low sensitivity may well be a loss of subjective dynamic expression, due in part to the requirement to absorb the increased power and the resulting thermal response.

Many of the better system design examples now include a form of waveguide loading (e.g., a shallow horn contour) for the HF unit. This increases efficiency in this driver’s
lower frequency range but also helps to somewhat narrow the directivity through the crossover region to better match the mid-range driver output. The result is a smoother power response which also improves sound quality. The shallow horn helps address the usual power peak found near the crossover point for the Mid-HF. This power step can develop where a wide directivity HF driver takes over from the mid-range section where the directivity of the larger driver is already narrowing.

In the light of the current level of performance for contemporary loudspeaker technology (Table 1.4) then goes on to suggest some idealized specifications for a spectrum of high-quality domestic loudspeaker systems. Concerning the amplitude/frequency response the close amplitude tolerances suggested have as much to do with the value of consistency as with sound quality per se, and for a given design, note that a given enclosure and driver format may not necessarily deliver a perfect ‘flat response target’ for optimum sound quality, since the latter criterion is also affected by the power response, and by how the speaker system as a whole interacts with the listening environment.

There are also several larger and more costly loudspeaker systems of wider bandwidth and higher efficiency, and thus greater maximum output than the examples given below, though these types are made in smaller numbers and suffer a more limited distribution. Somewhat idealized suggested specifications for contemporary loudspeaker systems are as follows:

**Table 1.4 Idealised loudspeaker specification.**

<table>
<thead>
<tr>
<th>Axial pressure response</th>
<th>60 Hz–15 kHz, ±2 dB (sine and/or 1/64 octave measuring bandwidth)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100 Hz–10 kHz, ±1 dB (when octave averaged)</td>
</tr>
<tr>
<td></td>
<td>(or closely compliant with an objective response target)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LF compensation for room gain</th>
<th>Output from 25 Hz to 70 Hz tailored to specified local boundary and to overall room conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off-axis response (up to 12 kHz)</td>
<td>Within 2 dB of axial output for ±20° vertical and within 3 dB up to ±45° lateral</td>
</tr>
<tr>
<td>Harmonic distortion (90 dB)</td>
<td>100 Hz–15 kHz, &lt; 0.3% (with 3rd &lt; 0.1%)</td>
</tr>
<tr>
<td></td>
<td>Below 100 Hz, &lt; 2% (with 3rd &lt; 1%)</td>
</tr>
<tr>
<td>Harmonic distortion (96 dB)</td>
<td>100 Hz–20 kHz, &lt; 0.5% (3rd &lt; 0.2%)</td>
</tr>
<tr>
<td></td>
<td>Below 100 Hz, &lt; 6%</td>
</tr>
<tr>
<td>Sensitivity (2.83 V)</td>
<td>Greater than 88 dB/W at 1 m, (90 dB level preferable)</td>
</tr>
<tr>
<td>Power rating</td>
<td>≥100 W peak programme</td>
</tr>
<tr>
<td>Impedance</td>
<td>8 Ω nominal, 6 &lt; Z &lt; 20 Ω, phase angle &lt; 30°, 20 Hz–20 kHz, (not less than 4ohm, &lt; to &gt; 30 kHz)</td>
</tr>
<tr>
<td>Maximum sound pressure (note application)</td>
<td>&gt;105 dB, unweighted at 1 m (domestic)</td>
</tr>
<tr>
<td></td>
<td>&gt;115 dB, unweighted at 1 m (monitoring)</td>
</tr>
<tr>
<td></td>
<td>120–130 dB, unweighted at 1 m (stage and PA application)</td>
</tr>
<tr>
<td>Size/application (approximate internal volumes)</td>
<td>Domestic: 25–50 litres</td>
</tr>
<tr>
<td></td>
<td>Monitoring: 50–150 litres</td>
</tr>
<tr>
<td></td>
<td>Stage: 100–200 litres and/or horn loaded</td>
</tr>
</tbody>
</table>
Even the exacting numeric targets set out above cannot guarantee high performance. The many aspects of driver integration, phase and amplitude, of resonance colouration, enclosure and driver, also enclosure diffraction, and issues of room matched bass alignment and tuning, are also crucial and do not appear in such specifications. Nevertheless, the attempt to meet a well tolerated specification is generally considered an important aspect of performance improvement, and not least for product consistency. And as noted previously, it is known that stereo image focus, which subjective quality is hard to quantify by measurement, does improve with closer tolerated pair matching.

The noted advances in quality in recent years are not confined to the high-performance end of the market: in fact, all loudspeaker systems have advanced significantly over the same period. For example, many of the causes of colouration in both cabinets and drive units have been identified and can now be adequately suppressed. Further key factors concern a better understanding of diaphragm behaviour through the application of finite element and similar analyses, and with the successful application to drive-unit manufacture of inherently well damped synthetic and composite materials. A sufficient variety of well-designed drivers and driver solutions are now available for the independent system designer. These cover specific sections of the audio spectrum over a range of different power levels and allow the designer considerable latitude when determining the size and cost for a given system. Larger manufacturers have the freedom to originate their own driver technologies and designs.

A key high-frequency unit identified in the success of a number of original BBC and several subsequent design derivatives was the Celestion HF1300. Designed around 1955 it proved suitable for medium power applications and was in fact first used by GEC as a ‘presence unit’ to augment the upper frequency response of their aluminum cone driver models dating from the 1950s, here fed via a simple crossover, a series capacitor. Some 35 years later, the driver was still employed in several high-performance systems. Ironically it was based on a 38 mm ‘pressure’ unit for a mid-frequency horn, an internal cockpit loud hailer for a battle tank, and was later modified for hi fi use as a direct radiator, notably by the addition of that characteristic, tangentially slotted ‘phase correcting’ front plate which extended the existing 9 kHz response limit to 13 kHz. Fitted with a lightweight 20 mm voice coil, the critically treated, one-piece, phenolic-doped cambic fabric diaphragm has a conical centre section, combined with an integral, shallow curved annular surround region, which also acts as the suspension. It is pistonic over the working range, and when correctly mounted, should be projected forward of the baffle front plane by 6 mm. Installed in the right system it helped to provide very natural speech reproduction with convincing sibilants and fricatives, a quality that still eludes numerous designs of more recent vintage, even at considerable cost. Many modern loudspeakers sound fine on music and close miked, compressed pop vocals but are insufficiently neutral or articulate sounding with naturally balanced vocal recordings replayed at a natural sound level. That failure is as much to do with the quality of many high-frequency drivers as the system tonal balance, and the associated crossover design.

1.4.1 Diaphragms: Materials and Consistency

There remains a major problem for drive-unit manufacturers, namely suitable diaphragm materials. Bextrene, a butyl rubber/polystyrene co-polymer, had proved highly successful for the manufacture of vacuum-formed cones, including those BBC
examples, and gained wide acceptance among the major UK drive-unit/speaker manufacturers. It was almost a chance discovery, as the material was originally designed for use in the production of low-cost, blow moulded packaging, for example, for chocolates.

However, in the more critical loudspeaker applications, experienced drive-unit manufacturers eventually discovered that mechanical and acoustical properties could show disastrous variations from batch to batch. The chemical industry which was supplying the product was not particularly interested in solving these problems as the requirements of the more exacting loudspeaker industry were minute compared to total sales for packaging. It became essential for a loudspeaker designer to carefully quantify the mechanical properties of a proposed cone material and to continue to do so for each batch ordered. Despite these technical difficulties, with careful design and good manufacturing quality control, such moulded polymer cones are generally superior to pulp/paper composition types, in colouration, uniformity of response and especially sample-to-sample consistency, a key issue for pair matching.

In recent years, various formulations of polypropylene have largely displaced the older Bextrene material though as for its predecessor, some characteristic material-related sound aspects may pertain, difficult to avoid entirely in completed designs. Cone polymers may also be improved by suitable fillers such as talc. That noted inherent sound characteristic, and also the pursuit of higher sensitivity has also led to renewed experimentation with lighter and more rigid composite or sandwich constructions, and also the application of resin bonded woven fibre skins such as glass, Kevlar, flax and carbon/graphite.

There are also further developments with treated paper pulp formulations of greater consistency and also using spun aluminum and similar metal foils. One extreme case employs aluminum cone membranes machined at enormous cost from solid billet. Despite the application of these many technologies, classic paper-pulp formulations remain very popular. Notable high performance speaker examples continue to be designed with pulp-based cones and may also use doped fabric dome drivers of established technology for the high-frequency range. Experience shows that there are many effective examples counter to the more popular design trends.

1.5 Influence of Improved Low-Frequency Analysis

As far as frequency response is concerned, the fundamental analysis of loudspeakers at low frequencies, here treated as the equivalent of a high pass filter, is considered to have been pioneered by Neville Thiele, and was first presented by him in 1961, noting that both Locanthi, Lyon and also Beranek had previously studied the subject in some detail, while Novak had carried out significant commercial development by the late 1950s using a comparable approach. Ted Jordan's own contribution to this theory should not be neglected, especially his matured view that smaller vented enclosures behave as complex non-linear modulators at higher sound levels, and that in general the sealed box form has greater parameter stability and consequently improved fidelity, at least for smaller enclosures, for example, those less than 10 litres.

The comprehensive analytical approach by Thiele was recognised for its true worth in later years, and the subsequent painstaking research on the subject by Thiele's graduate student, Dick Small, and later by others, has also proved to be of great value to modern
designers (Note the abbreviation ‘TS’, the Thiele-Small parameters for drivers at low frequencies.). Many theoretical papers by these and other authors have provided a remarkably complete analysis of low-frequency system behavior using filter network theory, this the one area of loudspeaker design where the results are largely calculable and predictable, if limited to within known linearity limits for drivers and the acoustic loading chosen.

Armed with such theory, and acknowledging that most modern system design software is largely based on it, there is every reason why any loudspeaker designer worthy of note should be able to produce a loudspeaker with an intrinsic low-frequency behavior which is fit for purpose.

Nevertheless, dispute remains concerning the subjective consequences of many of the higher order low-frequency tuned alignments, fourth and above, such as extended time responses and increased group delay. Some critics, including this author, take the view that audible error thresholds for group delay and colouration are frequently exceeded with many vented and related higher-order alignments.

Certainly, there is good evidence that the smaller, maximally flat, augmented fourth and higher-order systems do have aurally identifiable group delay, this detracting somewhat from music replay quality, and that this behaviour can also lead to significant level matching errors incurred when professionally balancing and mixing tracks with percussive low frequency content.

Still relevant in respect of its advanced design the highly successful KEF R104 II remained in production for 12 years from 1984, (see Figure 1.6) the low-frequency design founded on TS theory. It is a high-output, high-sensitivity speaker system

![Figure 1.6](image-url) An ingenious and commercially successful loudspeaker system with band pass low-frequency design and reaction force cancelled drivers. A laterally tapered, separate, partially decoupled sub-enclosure comprises a MF-HF symmetrical array (after KEF). (Source: Courtesy KEF Audio)
possessing fine dynamic capability and able to reproduce a very wide dynamic range to high output levels. The optional KUBE active equaliser, in practice rarely used, was an option to extend the low frequency response down to 20Hz (−6 dB, Q = 0.5), also to provide better group delay. (Use of this unit was often shunned as it did not appear to transmit the full sound quality of better audio amplifiers for some users.) The low-frequency design is coupled cavity, here with a second order roll off, consequently with good transient response and thus good timing. The design team was led by Laurie Fincham and the specifications included:

R104II:
Size: 900 × 280 × 415 mm, weight: 32 kg
Nominal Impedance: 4 ohms resistive (20 Hz–20 kHz), compensated.
Rated maximum power: 200 W programme
Amplifier Requirements: 25–200 watts per channel into 4 ohms
Frequency response: 55–20,000 Hz +/−2 dB at 2 m on design axis
Sensitivity: 92 dB at 2 m on reference axis for a pink noise input of 2.83 V
Maximum output: 112 dB on peak programme (see Figure 1.6).

1.5.1 Crossover Developments and Active Designs

While the vast majority of multi-way loudspeakers use passive crossover networks to separate and direct the filtered frequency ranges to the appropriate drive units, more recently, sophisticated electronic crossover techniques have given rise to further improvements for the modern generation of active crossover, power amplifier equipped ‘active’ loudspeakers. These are frequently used for near-field studio monitoring and small-scale public address. Although the idea is not new, historically active filters were awkward and expensive to execute for previous generations, here using valve amplification, and found little favour. Conversely, in recent years, the expansion of active-filter theory and the availability of inexpensive operational amplifier implementations, together with the low cost and high efficiency of transistor power amplifiers, have given renewed impetus to the active loudspeaker genre and many active multi-way loudspeaker designs have been produced for professional monitoring, while there are also some notable examples for domestic use. Still more recently full digital crossovers often of much higher order are emerging with a combined DAC and power amplifier, often a Class D switching type, one amplifier for each driver. There has been an explosion of such active designs for PA public address stage sound reinforcement and studio monitoring many with custom digital response correction and equalisation. Higher quality and greater maximum sound levels are benefits.

Given the substantial performance gains possible for active working, involving direct amplifier connection to the drive unit, it is something of a mystery that such technically advantageous design practice is not taken up more widely for domestic high-fidelity loudspeakers. One explanation is that hi fi systems represent a kind of train set for music loving adults where they can mix and match and upgrade audio components within a system, those items specifically and personally chosen for improved quality music replay in the home.

The widest application for active design is in PA, at a quality now advanced well beyond what used to be considered tolerable ‘public address’, and where even
Inexpensive two-way pillar mounted designs offer tolerably good sound at high-peak levels with the help of active electronics, and at remarkably modest cost. With the potential performance advantage seen in full measure, active loudspeakers, especially those with DSP hardware and a digital audio interface, are also assuming increasing importance in high-quality applications especially for studio monitoring. Considerable adjustability may be provided to achieve the most accurate rendition in the monitoring environment. Advanced DSP solutions are increasingly economical with gains in processor performance at reducing prices, and these readily programmable filters readily handle subtle system design and room interface issues in the hands of an experienced operator. These are frequently supported by sophisticated programs which can model even complex acoustic environments and their audiences and thus help optimize the loudspeaker radiation, directed response and delay parameters.

An example of a high-performance domestic, active design is the Meridian DSP 8000, an active floor-standing model of notably complete design provided with digital-only input connectivity, either via S/PDIF or a proprietary network source. Here performance transcends expectation at the price and size thanks to the advantages of full active design (see Figure 1.7).

The driver array (Meridian DSP800) is arranged over a slanted back front panel, the latter aiding time alignment for the mid and high frequencies and optimizing directivity. These are fitted to a decoupled upper assembly, this enclosure rigidly cross braced. The six LF drivers are opposed in sets of three, which together with extensive cross bracing provides a degree of force cancellation, the lateral formation avoiding fore and aft rocking which can soften image focus. Multiple Class A/B amplification equates to a

![Figure 1.7 Meridian DSP 8000, an, active floor-standing model.](image-url)
headroom which would otherwise require 1,000 W of external audio power. The DSP provides precision equalisation and crossover functions, driver matching, level alignment and room and location response tailoring. System and local remote control is provided while the digital audio and control input is via network cable. To maximize dynamic range a combination of analogue and digital attenuation is employed ensuring that the loudspeaker noise floor remains silent at low-volume settings.

1.5.2 Home Theatre Systems: Dolby Atmos

Another development which has supported increasing sales for the speaker industry is DVD /Blu‐Ray and similar, multi-channel–capable media formats primarily for home movies—so-called Home Theatre, for consumers. Where two channels sufficed for stereo sound, here there are typically 5.1 channels, which traditionally may be extended to 7.1 for high-end arrangements. A well reproduced centre channel is the vital component, delivering power, dynamics and high intelligibility to the subjects for the vital ‘dialogue’ channel feed. The performance of this centre section can make or break system performances.

Controller/processor amplifiers, ‘receivers’ of 7 channels, with up to 200 W per channel are not uncommon and these can make significant demands on some of the more compact speakers favoured for multi-channel domestic working, both for pure music recordings and for movies. The best of these installations comprises speakers of matched quality and performance, and where customers will bear a considerable cost for this particular quality of personal entertainment. Many of the more upmarket in situ installations have customized rooms with concealed and in-wall in ceiling loudspeakers.

With the introduction of Atmos™ by Dolby Labs, more complex multichannel systems have arrived, this format derivative of the ‘Dolby 70’ sound channel cinema standard, formulated to provide enhanced localization for sound source effects, especially overhead. Atmos kicked off with potential 128 encoded audio tracks and a resulting 64 possible loudspeaker drive signals. These signals can be adjusted for a particular movie theatre site installation to suit the location of each loudspeaker, floor, ceiling, (or reflected sources) in order to enable the required virtual source panning at higher precision, this including height. At the time of writing there are about 3,000 cinema locations with first-generation Atmos installed.

For domestic use, the Atmos cinema master has to be rendered to a fixed, spatially encoded digital channel carrying potentially 11.2 channels of rendered audio (the ‘0.2’ is for two subs). A home setup (Figure 1.8) typically comprises four overhead reproducers, front left and right and rear left and right, but with none in the corners. The front stage is provided by a centre loudspeaker, and then flanked by larger left and right systems, these ideally full range. A quartet of side and rear stand mount systems located near or above head level completes the arrangement. In a reduced arrangement, the front and rear speakers may have additional upward firing transducers to bounce the height information off the ceiling.

More recently, for less expensive home install, the overhead requirement has been sidestepped by adding upward facing drivers in the top panels of the left and right front speakers only. Here the mid to upper frequency sounds for those channels are designed as separate channels, their signals reflected from the ceiling above the listeners thus
aiding the impression of height and of overhead sound sources. Save for the front stereo channels, note that all the sound sources are now discrete pan potted mono channels, and are not phase related to each other.

### 1.6 Changes in UK Lifestyle are Affecting Domestic Audio Systems

Increasingly many UK consumers are finding that the more recent arrangements for living accommodation, where an increasingly open-plan approach to shared family entertainment prevails, precludes the classical approach to stereo reproduction. This traditionally advises a reasonably symmetric room arrangement for the two loudspeakers and with the listener(s) placed at the apex of the equilateral triangle so formed. The latter situation is now frequently becoming the exception, in the UK at least.

Some stereo enthusiasts may find an effective compromise in a family environment by embracing multi-channel home theatre movie systems where good stereo reproduction may still be possible, and in addition multi-channel surround sound music recordings may also be enjoyed. However, with multiple loudspeakers, and with the complex signal processing and amplification often required for home theater equipment there is often a loss of fidelity, and of precision for the front sound stage content and focus. The subtler high-fidelity aspects desired from first class sound reproduction are often diluted.

One manufacturer (Linn) is exploiting the programmability of modern digital processor active speaker designs to allow for programmed correction for offset and asymmetric locations, both for speaker and listener. Individual left and right loudspeaker adjacency to local boundaries is accommodated in the processor as is an asymmetrical placement relative to the listener, including time of flight correction at the listening seat. As is
increasingly common with modern active systems the individual drive units are closely characterized in production and matched DSP correction applied, to optimise response uniformity and sound quality.

Different customer choices of grille material and absorption can be corrected for, including the near-field reflection effects of the potentially dense tweed grill fabric on the driver output.

Another maker has created a large, powerful, primarily stereo application loudspeaker (B&O Beolab 90) with near omnidirectional capability, founded on a complex multiple driver array. Every driver has ample active amplification driven under DSP control to linearise the projected frequency responses, correct for location and room boundaries in respect of time delays and also control the desired user directivity and image perspective. In addition, for acoustically complex open plan larger room spaces, the output may be programmed by remote control wireless app control to optimise sound quality for listeners remote from the stereo sweet spot, e.g. in an adjacent breakfast area.

1.7 High-End Stereo Audio

A significant market sector remains for higher quality stereo audio systems, even if it is slowly declining. Audiophile purchasers of these often costly arrangements generally possess a fine and valuable collection of music recordings, physical media and locally stored HD material. Here a minority of enthusiasts are comfortable in spending considerable sums for top-quality stereo reproduction equipment. Professionals in the sound business may scoff at this market but many such audiophile customers are highly discerning and take considerable care over their purchases, and with the resulting installations. For example, one noted U.S. manufacturer, Wilson Audio, makes passive loudspeakers systems up to $200,000 a pair and recently explained that in the past four years they had sold 800 such examples at that price (and even one at $600,000 a pair!). With commensurate support electronics, audio signal sources and amplification, and excluding listening room improvement investment a supporting stereo system will add around $200,000. It is worth noting that there are about 18 loudspeaker makers on the international market fielding designs of roughly comparable quality and size, priced from $150,000 to $300,000 though likely not at the same sales volume (Avalon Acoustics, Focal, Magico, Gryphon, Gamut, Dynaudio, Martin Logan, Marten, TAD, Estelon, Kharma, Backes & Muller, Tidal, Perfect 8, AvantGarde, MBL, Sonus Faber and Wilson Audio).

What is frequently termed ‘High-End Audio’ includes this substantial market for high-performance loudspeakers mainly for stereo reproduction. In a few cases these costly product lines are also extended into full surround sound systems.

1.8 Sound Docks

Pioneered by Bose and selling in vast numbers, we have the eponymous music player unitary ‘dock’ incorporating loudspeakers, where a variety of portable media devices, music players and smartphones may be installed, conveniently parked and on charge,
with full connection to their multi-contact electrical interfaces and where the operational controls are also connected. In addition, wireless music streaming frequently becomes seamlessly integrated with more recent solutions employing WiFi and Bluetooth interfaces, and so the music playing, source/control device, no longer needs to be physically docked, except for recharging. iPods and iPads frequently may be local network linked and can act as a streaming source from the internet or from a WiFi-associated hard drive music store via the associated ‘app’ program, this a product specific intelligent remote control facility loaded on a mobile device.

Commonly such apps operate on the ubiquitous mobile phone and tablet platforms and for many designs the dedicated remote control provided for an audio product has been consigned to history. Literally hundreds of designs for ‘stereo’ music docks have become available, where compactness is often a key feature. High power, almost invariably highly processed, so called ‘spatial’ generating multi-amplified speaker systems are in-built, almost invariably operating with the two available channels despite the absence of the physical width, speaker unit separation necessary to develop a satisfactory stereo image. Often there is some sort of proprietary processing to attempt to enhance the image, though this processing also frequently impairs fidelity since there are more than enough phase problems with the compact multiple driver array concept usually employed, while such additional processing adds more aural confusion.

1.8.1 Sound Quality Issues for Docks

A majority have a sound quality which is disfigured by intrusive signal processing. Note the comparable custom seen for the out-of-the packaging image settings found for many flat-screen TVs. In this parallel situation, the colour saturation and contrast is set artificially high in manufacture, together with several intrusive image ‘enhancements’ to attract the shoppers’ attention in a crowded retail store. When the screen is finally installed in the home much careful resetting of numerous picture controls is necessary to try and recover the relatively neutral image rendition which is frequently possible.

For sound docks, extensive comparative listening tests have revealed that despite the severely limited low frequency headroom inherent with the necessarily miniature bass drivers, it is common to apply substantial bass boost, of some 5–8 dB (and often much more) at frequencies between 50 Hz and 150 Hz. In addition, on unpacking, the manufactured default bass equalisation setting usually invokes an additional loudness contour with still more low frequency boost. This is done so that in the noisy open plan sales showroom, the potential customer will be in no doubt that these small reproducers do offer some sort of bass. Frequently, no amount of adjustment by the user will permit an approach to a nominal accuracy and neutrality.

In other respects, such designers are also failing to make the most of these product opportunities. A design feature included to deliver the loudest sound, and by no means to obtain the best quality, frequently comprises heavy active limiting, audibly intrusive, to attain the absolute maximum undistorted sound level, more particularly when the circuits are overdriving the often already compromised lower frequency range. At increasing sound levels, this audibly invasive signal processing progressively cuts
back the bass bandwidth to prevent the system from entering unacceptable overload, subjecting the bass to increasingly aggressive compression, usually with readily heard attack and decay time constants. This audible bass pumping modulation is considered very damaging to musical expression. Where a table or near-wall reproducer should offer good articulation and timing with a low-frequency system Q of 0.5 to 0.7, the product market average provides Q values between 2 and 5.

Both this author, and not least independent listening panels, find the end result both irritating and unnatural, very often showing poor musical timing, which negates the very purpose for which it was designed, namely to play speech and music in a satisfactorily entertaining and intelligible manner. By no means is this view personal; it is shared by critical, experienced teams of listeners tasked with independently grading the comparative performance of these devices under controlled conditions. Also, sound docks are frequently used in kitchens where news and plays, reproduction of the spoken word, is an important aspect. The sound quality of many examples can be so poor that speech may be significantly unpleasant, annoying, and worse still, markedly inarticulate.

In addition, the ridiculous fashion of packing stereo channels reproduced via separate loudspeaker drivers where these are mounted in an enclosure 20 to 30 cm wide, results in very serious phasing and lobing across the horizontal azimuth for the usual monaurally dominant material, together with huge variations over angle for both the forward directed response and the resulting intelligibility. It is ironic that adding the description stereo, and providing two closely spaced paralleled channels, is one of the most damaging aspects of current design practice. Stereo enhancement processing is added to try and enhance the result which is frequently and boastfully employed, but serves only to add still more phase distortion and subjective roughness, further impairing clarity and intelligibility.

Nearly every audio brand has got involved in this wirelessly linked sound box market, together with newcomers from the computer accessory arena, and not least a handful record producers and entrepreneurs, even guitar speaker makers. In the UK, the sales of docks now well exceed the hi fi stereo separates market by market value, which fact also highlights the relative decline of those dedicated, higher-quality component stereo systems. For the world market, total turnover by value is in the tens of billions and must be taken seriously by the audio industry. While the performance aspirations for docks are clearly more limited than for separates hi fi, operating with small 9 to 12 cm bass drivers in highly equalized and for the most part very small enclosure volumes, I consider that the overall objectives for high-quality sound remain important and relevant for these devices. Some famous and well-established loudspeaker companies are important players here and a few do try to contribute to the art of audio design in miniature.

Here, well-founded audio engineering experience can usefully help differentiate product performances. Good practice for hi fi loudspeaker design is equally applicable to docks. Particular engineering skills will include thermal modeling, predicting and controlling dynamic performance near damage limits, and defining allowable margins for amplifier clipping. Also to be considered is the dynamic control of power with frequency, for example, scaling back bass extension and/or overall level towards the last few dB of available headroom, here working against a sensible perception model for audible distortion, and with well judged overload time constants for frequency and sound level. Docks now invariably include digital audio interfaces, including wireless transmission of audio between devices, for example, for synchronous
stereo operation as well as multiroom working, and for user control, particularly where some DSP resource is usually available. This facility may also provide scope for some of the dynamic signal processing described, but this must be exploited with discretion and backed by careful listening tests. For some examples, the lower-cost DSP chips employed may not have enough processing power to do much system control of subjective value.

Very few such products cannot benefit from some tasteful and properly considered audio processing, such as advanced dynamic, programme headroom matched equalisation. At the outset, the system certainly may be beneficially engineered and configured for maximum intrinsic efficiency, loudness and potential bandwidth, and not necessarily for an intrinsically flat response. Then the product can be electronically equalized via the DSP facility for an optimally balanced, natural sounding frequency response, this judgment also taking account of the intended placements and locations settings in a room. Settings for alternative locations would be a valuable feature. The inclusion of such versatile functionality will also allow valued input from the user concerning choices for ‘tone’ control and for setting both ‘loudness’ equalisation and not least room placement-related settings.

Independent tests have revealed that for a number of docks sound quality may be improved about 10% when fed from the alternative of a wired, line level signal. Unfortunately, a number of the less expensive types, when using Bluetooth and similar wireless connections to the music source, have audibly impaired sound quality. Designers need to listen more critically to these bought-in radio chip solutions for wireless connectivity and see whether the performance on offer is sufficient.

1.8.2 Sound Bars for Flat-Screen Displays

What could be regarded as an offshoot of sound docks are sound bar ‘combination’ speakers, intended for placement adjacent to or underneath including on the wall, and optionally, even supporting, large flat-screen televisions. While relatively compact, these generally slim, laterally elongate loudspeaker units attempt to reproduce centre channel plus left and right channels, often with surprisingly highly powered, summed, single-channel, low-frequency sections. Enhancements include signal processing for widening the stereo image; often using HRTF related filtering to generate virtual rear channel effects. These image ‘widening’ filters often degrade timbre and sound richness, and also can be fatiguing over longer periods, though some solutions may be surprisingly effective. These devices also frequently employ dynamic envelope processing optimizing low-frequency headroom and for dynamic control of frequency extension to try to maximize subjective performance.

In particular, many such all-in-one boxes accept digital multi-channel inputs, for example, via optical S/PDIF from a smart-screen TV and can readily process these for enhanced spatial and multichannel operation. Under subjective testing only a very few of these products were found to be effective on sound quality grounds.

As with all speaker systems the final voicing should be carried out in representative local acoustic conditions, applying the usual experience and common sense when judging sound quality. It especially important that speech be highly articulate and neutral, for the benefit of news broadcasts, and also for the highly informative, mainly
dialogue, centre channel important for movie reproduction. Nevertheless, soundbars are very big sellers and are commercially very important. Many international 'stereo' loudspeaker makers are now active in this field, this involvement helping to maintain turnover.

1.9  Headphones

There has been also been an explosion in the headphone and earphone market, largely associated with the portability of miniaturised music players with good audio performance, these players now invariably incorporated in portable electronic pods, tablets or 'pads and not least the ubiquitous and versatile smartphone.

Many speaker makers have now joined this headphone party where their skills in electroacoustic modeling are applied to these closely ear coupled miniature reproducers. Many transducer technologies are found here, including electrostatic, ribbon, magnetic planar, moving coil and cone, Heil folded ribbon and more recently the traditional balanced armature principle. Both pressure (sealed back) and velocity (open back) types are evident. More recently many cordless Bluetooth linked types have emerged adding convenience, and the costlier examples may also include sophisticated noise cancellation. With increasing miniaturization of the electronics, headphones are becoming increasingly intelligent and may have sophisticated tone controls, even to the extent of an automated DSP to measure the users’ individual ear canal impedance and thus equalize the design to a more uniform in situ frequency response.

The sophistication of these processors has also facilitated the valuable addition of increasingly effective noise cancellation, some implementations using multiple microphones whose data collection includes phase, for more effective cancellation. Regardless of some loss of quality in the transmission path, wireless designs are quickly dominating the main market, but not so much for those intended for audiophile use. The wireless link, often Bluetooth, is constantly improving for the costlier examples.

1.10  Advances in Pro Audio

Significant system design sophistication is increasingly evident in the professional field, especially for sound reinforcement. The opportunity presented by arrays of active drive loudspeaker elements (Figure 1.9) which may be individually controlled via DSP processing for phase, delay and frequency to create in this working environment well-computed well-directed sound fields of considerable bandwidth and improved quality, has revolutionised the public-address market. Much better fidelity, with precisely controlled selective directivity coverage, has been achieved, even for some of the most acoustically awkward stadia and locations. In addition, under dynamic control, these systems may be rendered audience adaptive, allowing optimisation for different audience sizes and distributions, and may also provide sophisticated programmed theatrical, directional effects, together with identifiable sound zones, to interact with and enhance creative events.
Notes


Bibliography


AES (Audio Engineering Society) A considerable number of the A.E.S. journal papers cited in this book have been published as follows in four volumes by the Audio Engineering Society: The AES also holds an electronic library of past convention papers and papers published in the AES Journal, many on electroacoustics and loudspeaker aspects.

LOUDSPEAKERS VOL. 1 edited by Raymond E. Cooke. Sixty-one papers, covering the years 1953 to 1977, written by the world’s greatest transducer experts and inventors on the design, construction, and operation of loudspeakers.


LOUDSPEAKERS VOL. 3–Systems and Crossover Networks edited by Mark R. Gander. Forty-two papers with comments and corrections published on this specific area of loudspeaker technology from 1984 through 1991. With a companion volume on transducers, measurement and evaluation, this publication extends the work of the first two volumes on the important topic of loudspeakers. An extensive list of related reading is included.
