Proceedings of the Institute of Acoustics

CINDERELLA GOES TO THE BALL
- Remedying years of neglect of loudspeaker fundamentals

John Watkinson

Celtic, 2,Hillside, Burghfield Common, Reading RG73BQ

INTRODUCTION

In a paper presented at Windermere in 1994 I suggested that in many fields audio had reached near perfection whereas loudspeaker design remained an area for research. Since then I have, with my colleague Richard Salter, undertaken a rigorous yet detached review of loudspeaker technology. We have established what is necessary in a quality loudspeaker, and set out to build the most accurate loudspeaker possible as an academic exercise. We were not prepared for some of the experiences we have been through, many of which were little short of astonishing. We propose to share some of these experiences here.

Following a year of research and development the performance of technology demonstrators is so far in advance of the prior art that it has been decided to commence commercial production under the name of Celtic. One patent has already been applied for and a further application is in progress.

We did not actively set out to be loudspeaker designers let alone to become manufacturers. Our initial involvement stemmed simply from dissatisfaction with the then state of the art. In fact the ability to take a global look at loudspeaker design from a detached viewpoint has been a great blessing. It has been possible to sort the traditional from the rational and accepted truths have been questioned both by reasoning and practical experiment.

TRADITION

It is demonstrable by simple measurements that today loudspeakers form a weak link in the audio chain. It is widely accepted that flat frequency response and low linear and non-linear distortion are two important requirements (among others) in audio quality. It is odd that these criteria are suddenly abandoned when loudspeakers are considered.

CINDERELLA GOES TO THE BALL

Today several brands of microphone are capable of producing electrical signals which follow the acoustic waveform very accurately. The polar diagram of a microphone is critical to the tonality and high quality units have a wide range of directivities which are essential to the skilled user. For stereophonic use it has been theoretically and practically proven that the directivity pattern must be substantially independent of frequency if image stability is to be obtained. A loudspeaker is only a microphone in reverse and many of the same requirements are present. Although the requirements for directivity have been documented for decades, again these criteria are abandoned in most loudspeaker products.

A digital recorder has no sound quality whatsoever; the quality is determined by the convertors. Today's better convertors display excellent phase linearity, flat frequency response and distortion characteristics which are actually difficult to measure.

It is possible to deliver to the input of a power amplifier a recorded waveform of surprisingly high quality. Many of today's power amplifiers are capable of signal performance which was once only achievable at signal level. In comparison with the quality typically maintained throughout the rest of the chain, the performance of most loudspeakers is miserable and presents a quality bottleneck. Today, most domestic hi-fi systems and many professional installations represent poor value for money because too much has been spent on overspecified electronics and not enough on the loudspeakers which are consequently underspecified.

We have confirmed the following problems from which many of today's loudspeakers suffer. These are not subtle points for academic debate, but instead are glaring defects which are audible to non-technical listeners.

The reflex loudspeaker and its relatives the transmission line and bandpass speakers only work properly on continuous tone. It is surprising that this is considered acceptable when the information in music is conveyed by transients. Tuned loudspeakers cannot have minimum phase and are utterly incapable of reproducing the input waveform accurately; they produce linear distortion. Low frequencies lag behind high frequencies audibly rendering the reproduction of any percussive instrument quite unrealistic. This is documented by Moore [Ref. 1]. These periodic short cuts were developed when electronics was expensive and amplifiers were limited in power. Today their only merit is in low cost applications.

Such a conclusion is not difficult to reach philosophically. For high quality, Loudspeakers ought not to have an periodic behaviour; that is the job of the music. Accordingly if realistic reproduction is required, economy measures such as tuned or ported loudspeakers have to be ruled out. Low frequency reproduction must be minimum phase as we shall demonstrate.

The dome transducer looks intuitively right because the diaphragm is a section of a sphere and it would appear to the casual onlooker that it would radiate sound uniformly over a wide angle. As Kelley points out, [Ref. 2] this is a myth. The dome moves on one axis only and this is a far cry from the ideal pulsating sphere which it superficially resembles. In fact the dome transducer is precisely the opposite of what is required. In order to have reasonably constant directivity, the working radius of a diaphragm must reduce with rising frequency. A cone driven from the centre can do that, whereas the edge driven dome cannot. A direct consequence of the flawed concept of the dome is that it will never be able to maintain acceptable directivity over as many octaves as a cone. The main advantage of the dome is that the coil area is large and that cooling is easier where high SPLs are anticipated. Whilst this can be justified for some professional applications, it is hard to see any reason to use domes in domestic apparatus.

Exepting doublet loudspeakers, in all practical designs the area of the cabinet walls eclipses the area of the cone(s). Thus relatively small displacements of the cabinet can produce significant volume velocity resulting in colouration. In the search for rigidity, the conventional flat sided box-shaped loudspeaker has no merits whatsoever. Flat panels are the weakest structurally and are conspicuously absent in automotive, aerospace and marine design. Their persistence today is quite extraordinary. Olson [Ref. 3] showed that the rectangular cabinet is sub-optimal because of diffraction at high frequencies. The on-axis response is rendered irregular and off-axis response even more so. Far from being obscure, Olson's work is cited in books by Colloms [Ref. 4] and Borwick [Ref. 5]. Compounding the audible shortcomings of most of today's box loudspeakers is the almost total lack of aesthetics. With a few notable exceptions, today's loudspeakers will not win any beauty prizes and it is hardly surprising that the lady of the house often refuses to tolerate anything other than the smallest speakers tucked away on bookshelves.

CINDERELLA GOES TO THE BALL

It is not difficult to show that the bookshelf is the last place on earth in which a loudspeaker should be located. A loudspeaker should be clear of reflecting surfaces, including the floor, yet most compact speakers are sold without stands. The consumer cannot be expected to know how speakers should be positioned, yet little positioning information accompanies most products.

The continued existence of the passive loudspeaker must surely be due to tradition. Looked at impartially, the passive crossover causes nothing but grief. It is vital to make the high and low-pass outputs of a crossover complementary so that if summed the original signal results. This is virtually impossible with a passive crossover, but is a trivial problem with an active crossover. It is very difficult to separate the desired reactive action of a passive crossover from the undesired reactive action of the transducers. In an active system this problem does not arise. If high quality is required, then the finest power inductors and capacitors must be used in a passive crossover of some complexity. To provide definitive audio quality, the passive implementation will simply be more expensive than the active. We should bear in mind that the first commercially available moving coil speaker, due to Rice and Kellogg, was active.

Exposure to live sounds confirms that the reproduction of most loudspeakers is simply unrealistic. Whereas the live version consists of a multi-dimensional reverberant sound field, the direct reproduced sound is usually curtailed to a single forward axis. The sound quality off that axis is invariably poor and accordingly the reverberant field in the listening room is unsatisfactory leading to an unnecessary "sweet spot" where the unfortunate listener must remain. Again the problem is well documented; the deliberations of Baxandall [Ref. 6] being particularly relevant. The spacious, open, sound of Walker's Quad electrostatic loudspeaker is legendary, yet most people think that is a characteristic only of electrostatic speakers and make no effort to emulate it.

The most astonishing point is that all of the above is well documented; in many cases some time ago. Our research showed that there is no fundamental reason for this sad state of affairs. We found that difficult to believe, but eventually did believe it after our research loudspeakers, based on the criteria mentioned, performed astonishingly well.

It is a simple but unfortunate fact that loudspeaker design has become so deeply stuck in the mud that the application of four wheel drive will be needed to free it. The fact that designers cling to these outmoded and discredited technologies can only be due to a lack of vision.

CINDERELLA GOES TO THE BALL

THE TECHNOLOGIES

Whilst anyone can complain about the current state of affairs, it is more acceptable to demonstrate an alternative. This means studying the design problem. As yet there is no practical means to move air directly. For the forseeable future we must first vibrate a diaphragm. Producing precisely controlled vibration requires a knowledge of how masses move. Classical mechanics and physics tell us enough about electromagnetic and electrostatic actuation of diaphragms. Accurate control requires suitable electronic circuitry which we must be able to design. The principles of servomechanisms must be followed if our vibrating system is to be accurate and stable. To follow what goes on inside the speaker we need to know thermodynamics because we are compressing a gas, and it matters whether we do that isothermally or adiabatically. We further need thermodynamic knowledge to create provision to dissipate the heat from our inevitably inefficient transducers.

As listeners we are primarily interested in what happens outside the speaker; in the far field to be precise. It is the job of the cabinet to separate this from what goes on inside. The job of a loudspeaker cabinet is to do absolutely nothing. It must be utterly inert and resist the reactions from transducers and the internal pressures without any movement or flexing. A basic knowledge of structural engineering and materials science will help to design a suitably rigid structure.

At low frequencies it is primarily the volume of the speaker cabinet which concerns us, whereas as frequency rises the shape becomes more important. In order to anticipate and control the high frequency sound output of a loudspeaker it is important to have more than a passing acquaintance with the wave or diffraction theory of acoustics. The concepts of coherence, phase and interference become crucial to the creation of a useful polar diagram. In fact light behaves in exactly the same way as sound, simply on a different scale, because it is a wave motion. A knowledge of wave optics is extremely useful in loudspeaker design because it allows the diffraction behaviour of cabinets to be predicted. Finally the appearance of the finished product is important.

My approach to loudspeaker design is to turn problems into opportunities. Wherever a bottleneck exists, the tangible returns for a given effort are greater. In other words there is scope for a dramatic improvement in the overall performance of sound systems by paying attention to a few key areas.

CINDERELLA GOES TO THE BALL

THE DEVELOPMENT

Our research showed that significant improvements were technically achievable. One project was to produce the most accurate loudspeaker possible by meeting as closely as was practicable our theoretical criteria. This loudspeaker was to be used as a reference and to act as a technology demonstrator. To save time the Quad ESL-63 was considered as the midrange and treble unit as it is very nearly ideal. There are several key reasons why the Quad sounds so good. It radiates backwards as well as forwards and has an extremely wide and smooth directivity characteristic so that it correctly excites the room reverberation to create an impression of the original sound field. The lack of a conventional crossover between displaced drive units means that there are no discontinuities in the horizontal or vertical polar diagram to disturb the uniformity of the sound field. The ESL-63 also displays minimum phase, although that requirement was not well understood when it was designed. Finally it has remarkably low distortion. The only shortcoming of the ESL-63 is that it cannot reproduce low frequencies at realistic SPL. If such frequencies are present on the input they cause excessive diaphragm travel which results in intermodulation distortion or shutdown. The solution is to provide an LF unit which offloads the ESL-63 at low frequencies. Diaphragm excursion is reduced and a significant increase in SPL is obtained with low distortion. As we shall demonstrate, the widely held view that electrostatic loudspeakers cannot produce high SPL is a myth.

The design of the LF unit was a tough job because it has to be minimum phase and have very low distortion in order to complement the transparent characteristics of the ESL-63 and to give realistic reproduction of percussion. A further requirement was that it should be compact. The Quad is already a large unit and a dramatic increase in size was undesireable.

An entirely new LF enclosure and amplifier topology was devised and we have applied for patent protection. The new topology produces low distortion and minimum phase down to arbitrarily low frequencies in a hitherto impossibly small enclosure and renders acoustic suspension, reflex, bandpass and transmission line loading obsolete except as economy measures. Unlike tuned alignments, below the working range there is a gentle monotonic roll-off.

The new toplogy allows a compact subwoofer which does not increase the footprint of the Quad and which blends with it aesthetically. The Quad is raised only nine inches by the subwoofer beneath. This raises the centre of the Quad's phased array to the height of the ears of a seated listener.

The crossover had to be complementary to guarantee a seamless transition. This requirement and factors such as precise LF diaphragm control demanded an active implementation. Critical listeners have been unable to determine the crossover frequency. The combined unit displays minimum phase from 20Hz to 20kHz making it the most accurate and lowest distortion full range loudspeaker ever built. This unit has proved so successful that it is to be made commercially available. An indication of the validity of our rigorous design procedure is that the subwoofer worked straight off the drawing board. The only modifications which will be made concern production engineering.

As will be demonstrated, this conversion has transformed the Quad into a device which can tackle a wide range of tasks. For domestic listening, all types of music can be reproduced at realistic level. The precision and imaging make it ideal for classical mastering and monitoring. In fact the bipolar dispersion characteristic also makes it suitable for high quality sound reinforcement as positioning the microphones in the lateral null minimises feedback.

THE FUTURE

Our technology demonstrator indicates possession of the above listed set of skills for the development of advanced loudspeakers. Such skills must exist elesewhere but apparently without the vision to combine them creatively. To complain that quality loudspeakers are too difficult or too expensive to design is to miss the point completely. The truth is that the only worthwhile goal is the impossible because the market for the possible is already over subscribed. The hybrid electrostatic/electrodynamic speaker we have developed shows that a seamless integration of the two technologies is as possible as it is necessary. The phased array electrostatic technology pioneered by Walker has many advantages and is more easily implemented with modern electronics. If such a device were designed from the outset as part of a hybrid speaker the freedom from having to reproduce LF would remove a number of constraints which we had to accept by using a relatively standard Quad. In particular a hybrid designed from scratch will be more compact and therefore command a larger market. The neglect of the electrostatic principle by all but a few manufacturers is odd and deserves to be remedied. However, it has to be accepted that the hybrid electrostatic speaker will never be as compact as a fully electrodynamic unit. The adoption of the new LF topology we have invented allows full-range electrodynamic speakers of unprecedented small size. Consequently we do not see these approaches competing as they will appeal to different markets.

CINDERELLA GOES TO THE BALL

What Celtic is doing is to capture the high ground of advanced electrostatic and electrodynamic speaker technology by producing definitive designs which not only have exceptional sound quality but which have a pleasing appearance. The curvaceous outlines which are necessary to control diffraction and eliminate enclosure flexure present new opportunities to industrial designers. If a loudspeaker can justify its presence by its aesthetic qualities even when silent it may be able to move from the bookshelf to a more conspicuous place where it has a better chance of creating a sound field. Only with such properties will surround-sound with television become a success.

Once the high ground is secure the technology developed there can migrate to a wide range of applications creating a substantial manufacturing opportunity. The economic conditions are now right for such a venture and with Britain's reputation for quality audio it will not be difficult to enter export markets. In these days of multi-media and home theatre it seems particularly appropriate to observe that it is only with vision that sound advances.

REFERENCES

Ref.1. B.C. Moore. An Introduction to the Psychology of Hearing. Academic Press
Ref.2. S. Kelley. Transducer Drive Mechanisms. Chapter 2 of Borwick, op. cit.
Ref.3. H.F Olson. Acoustical Engineering, Professional Audio Journals Inc.
Ref.4. M. Colloms. High Performance Loudspeakers. Pentech Press.
Ref.5. J. Borwick (Ed.) Loudspeaker and Headphone Handbook. Focal Press.
Ref.6. P. Baxandall. Electrostatic Loudspeakers. Chapter 3 of Borwick, op. cit.