

# **Hi-Fi** **WORLD** **SUPPLEMENT**

No. 19 DECEMBER 1995

**BOXMODEL -  
LOUDSPEAKER  
CABINET DESIGN  
ON THE PC**

## **DIPOLE BASS FOR THE QUAD ESL-63 ELECTROSTATIC**

**BOOK REVIEWS -**

**ELECTROSTATIC LOUDSPEAKER  
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**THE LOUDSPEAKER DESIGN  
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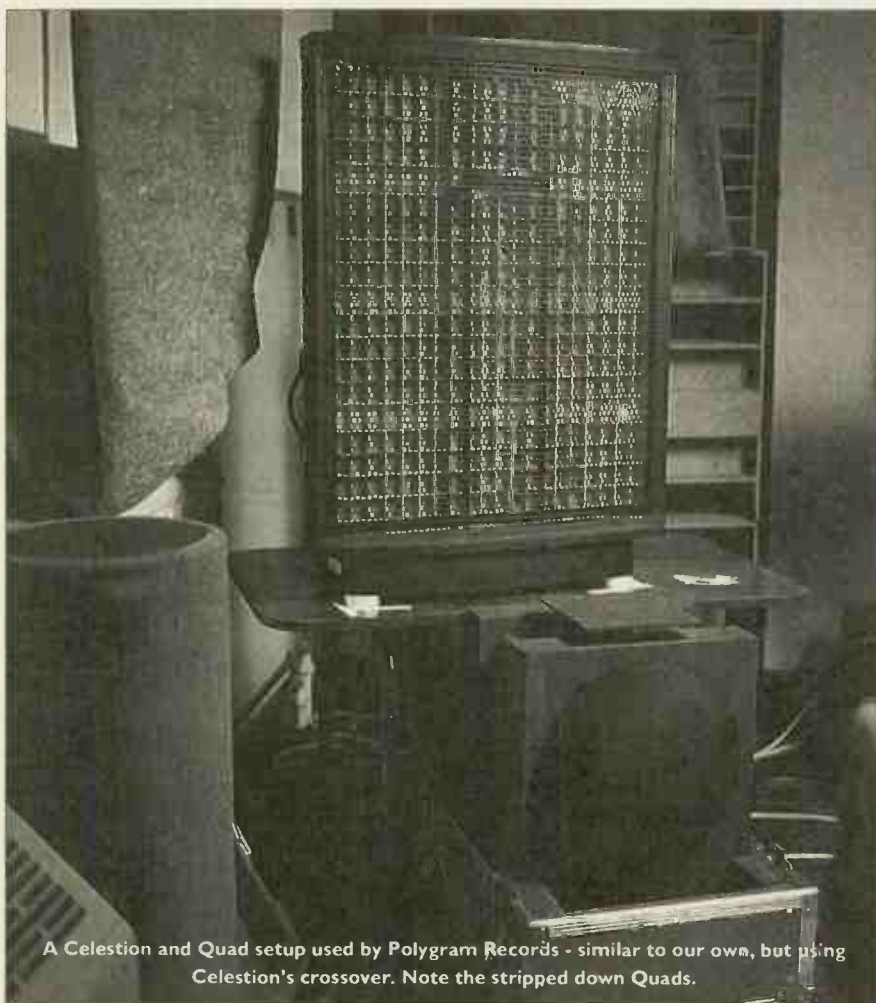
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**FREE D.I.Y. SUPPLEMENT No. 19**

# A SUBWOOFER FOR QUAD

**Prodded by yet another reader's request, Noel Keywood describes his adaption of the Celestion SL-6000 dipole subwoofer to match the Quad ESL-63 electrostatic loudspeaker.**



A Celestion and Quad setup used by Polygram Records - similar to our own, but using Celestion's crossover. Note the stripped down Quads.

**Q** I am a relatively new reader of 'World'. However, I have purchased some back copies from the 1991 era, including Issue No.1.

It is clear from the 1991 issues that a combination of the Quad ESL-63 and Celestion SL6000 was one for which you personally had a great affinity. The most interesting articles and correspondence in the March,

September and November 1991 issues are illuminating as to the potential of the SL6000 and convinced me that they would be worth enduring some pain in setting up in a listening room.

Theoretically speaking, the benefits of avoiding boxes for any speaker has to be a majorly positive factor in the quality of reproduction. The two speakers can apparently independently give outstanding mid and treble quality and

transparency (ESL) and bass depth (SL6000) unapproached by boxed subs. You do however point out eloquently in the November 1991 issue that there is a dropout zone between the two units (100Hz to 270Hz). You opined that you would be marketing a dedicated surface mounted electronic crossover to get over this problem.

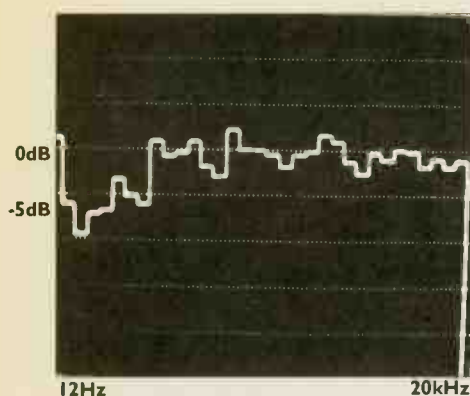
My system comprises Micromega Stage I, Michell Argo/Hera, Quad 606/II and Celestion Ditton 44s, with my own constructed external crossovers (Solen caps & RATA inductors).

I have the following questions, to which I would be grateful for your answers:

Did you progress with the design and marketing of the crossover? Are there any other articles from past issues that comment on the above pairing? You write currently that you use modified ESL-63s in your listening tests. What modifications have you made? What differences in sound quality would I experience between ELS and ESL-63 speakers? Do you have any articles/reviews on the Gradient sub for Quad ELS?

**Jonathan Ling  
Blackheath,  
London.**

Since you want to "endure pain" I'm sure we can oblige! This project is painful, expensive, and frustrating in its obscure complexities. Anyone that makes it past the finishing post will reap rich rewards. What it gives you, I've confirmed by measurement, is a loudspeaker that runs from 5Hz smoothly up to 20kHz.



Frequency response of the Quad and Celestion together reaches down below the 12Hz of this analysis.

Better still, it isn't a barrenly theoretical achievement. The combination is truly awesome to hear; it really does offer a sound that is quite extraordinary, not just a different type of squeak.

We're talking about getting the best from the Quad ESL-63 electrostatic which, as enthusiasts will know, has one of the smoothest and most natural

difficulties remain. This project fell by the wayside originally when Celestion stopped making the SL6000 open dipole subwoofers. They were heavy and cumbersome (barely liftable), had a poor electronic crossover/EQ box and were expensive, so commercial success was eluded. In my view they are an interesting idea with loads of potential, but Celestion's iteration was compromised, if fantastic in basic performance.

Anyone wanting to assemble this hybrid all-dipole / no-box system will either have to find a pair of second hand SL-6000s or build their own equivalent. Since a simple bass dipole comprises a bass unit on a baffle, it isn't difficult, but experiment will be needed to tailor my crossover circuit to it. I believe there's enough information here to get you acquainted with the problems and the advantages of bass dipoles, a very rare and peculiar form of subwoofer with great strengths.

Electrostatics and open-dipole bass

pass) of the crossover has a lot of equalisation built in, so test equipment to measure frequency response is essential - not expensive these days.

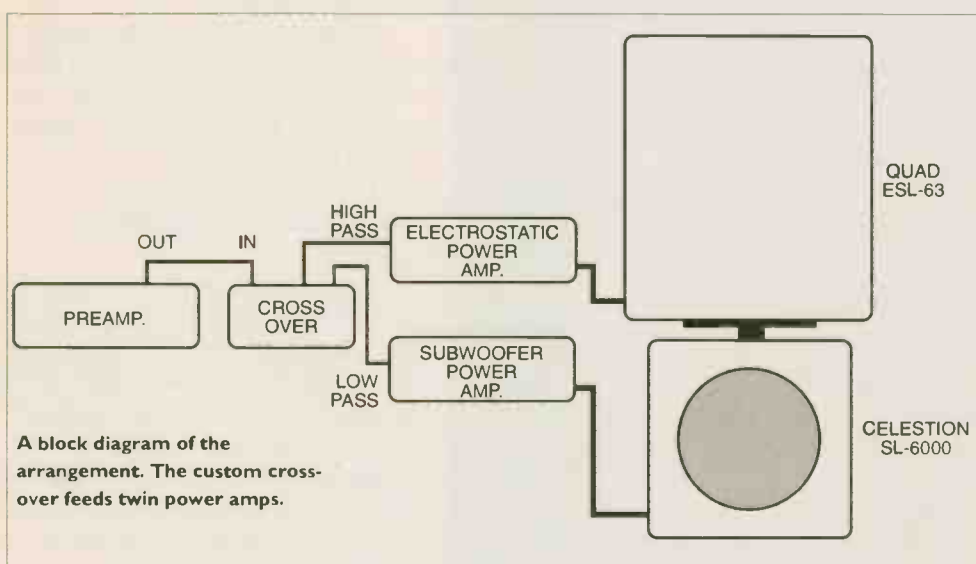
Bought new this set up is costly. But there are a lot of Quad owners around who already have half of it. And there are enough Quads about for them to be available second-hand too. Although the bass section will need experimenting with, there are hours of fun here, plus a potentially great end result. All that's needed are a pair of hefty bass drivers if you build your own bass baffles - nothing too expensive. So overall cost depends very much upon circumstance. I shouldn't forget to point out that Celestion designed the SL-6000s to go with their SL600 monitors. Similarly, the bass section here could be used with dynamic speakers other than Quad's.

I found satisfaction in running a loudspeaker that achieved so much without a cabinet in sight. This radical proposition offers an appropriately different result, one that showed me just

how many preconceptions characterise speaker design. Endless research has been carried out on enclosures of all sorts; that enclosures aren't necessary never gets consideration. It's quite an important realisation, one with some interesting commercial implications too. What if the Japanese developed and commercialised a speaker with no cabinet, using just a rigid plastic front instead? It would devastate the speaker market. I strongly suspect that the equalised dipole (open baffle) loudspeaker, with development, could be turned

into a commercially viable loudspeaker. The open-dipole subwoofer is a most peculiar beast. I know of very few manufacturers who've ever built or considered building such a speaker - and most that have walked away in the end! All credit to Celestion for trying. Here's a simple description of the operating principle and main features.

In principle the open dipole is just a bass driver mounted on a small baffle. There is no cabinet whatsoever. Below a frequency where the front-to-back distance of the driver, around the baffle



presentations of any loudspeaker, plus unmatched imaging. The subwoofer adds much needed bass, in this case including sub-bass down to the seismic movement zone. Furthermore, I carefully ensured bass signals were not handled by the Quad, allowing it to go louder without strain. The whole caboodle is larger than life in every sense.

Although the circuit published here took months of acoustics measurements and listening tests to develop (carried out back in 1991), some practical

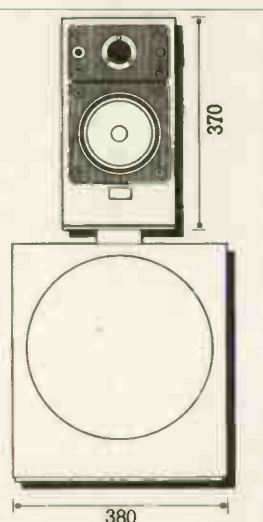
units definitely have a future in our view. Although the subwoofer (low pass) section of my crossover is very specifically tailored for the Celestions, it could be modified for an open baffle subwoofer. However, this is entirely down to the home constructor.

To tackle this project you will need some knowledge of electronics and, probably, Don Lancaster's Active Filter Cookbook (contact Modern Book Co., Praed St., Paddington, London W2. Tel: 0171-402-9176). The bass section (low



# CELESTION SL-6000 DIPOLE SUBWOOFER

Specifications	
Type:	Double dipole low frequency array.
Drive units:	Two 12" dia. long throw ultra linear units.
Sensitivity:	Matched to SL600, adjustment available.
Dimensions:	Height (inc. SL600) 825 mm
	Height to stand top 455 mm
	Depth 536 mm
	Width 380 mm
	Base 310 x 380 mm
Weight:	Unpacked 76lbs 34.5kg
	Packed 86lbs 39kg



(twice baffle radius, or baffle diameter) is half the wavelength of the signal reproduced, cancellation between the forward and rear radiation (they are out of phase) starts to occur, causing output to drop by -6dB per octave. Since to hit 40Hz, the lower limit of most box speakers, would mean building a baffle 28ft in diameter, it's not surprising that most people opt for a closed box.

An alternative is to use a small baffle and apply compensatory +6dB/octave gain in the amplifier, to cancel out the acoustic cancellation. That's what Celestion did with the SL-6000, albeit using twin drivers and some unspecified (but patented) modification to improve performance.

The potential benefits of this system are fascinating. There's no tuned cabinet to impose its own sound and lower frequency limit. So bass output is even and reaches down low. In fact, the lower limit is set by the free air resonance of the driver. The SL-6000 did, as I've already explained, actually go down too low - to 5Hz! The only other unit to get close is the big REL Stadium subwoofer, by the way. So open dipole subwoofers are effective in this respect, ignoring other matters such as power handling, cone travel, etc.

The SL-6000 subwoofers came with their own crossover and equalisation box, which I found unsatisfactory. It was necessary to re-equalise the SL-6000 subwoofers to overcome certain problems; my crossover replaces

Celestion's. It's rather unusual, being a fourth-order section 'tuned' to meet various criteria, but it is reasonably simple electronically.

I investigated three main areas for this project:

## 1) SUBWOOFER-TO-QUAD MATCHING

## 2) OPEN BAFFLE SUBWOOFER EQUALISATION

## 3) OPEN BAFFLE SUBWOOFER ROOM ALIGNMENT.

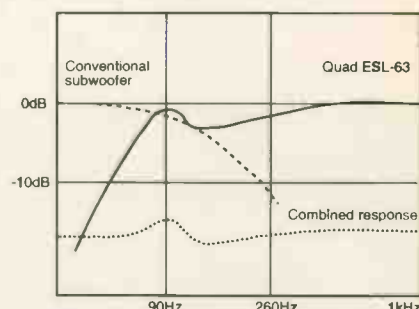
# 1) MATCHING

### Quad ESL-63

The Quad ESL-63 and the first ESL (57) have light bass because cancellation of forward radiation against backward radiation starts to occur at 260Hz, a frequency determined by the smallest panel dimension of 66cms (width). The rate of roll off depends upon positioning within a room, least loss occurring when placed on the floor and against a side wall, both of which can be thought of as panel extensions. On stands, however, the Quad's roll off in the bass is marked. There is some lift at around 90Hz where resonance of the driver/dust cover film

occurs. This augments what is otherwise a lean sound, adding a little extra weight.

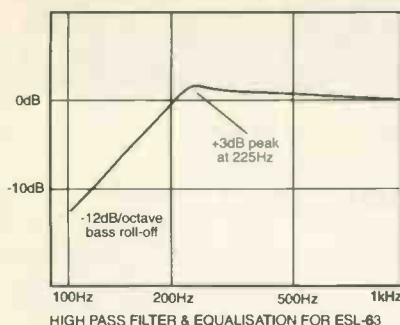
I've drawn the ESL-63's low frequency response in outline (see diagram). It is a classic electrostatic response, by the way, not peculiar to the Quads. You can see from this that it is impossible to perfectly integrate a subwoofer. There'll always be lumpy bass and a very obvious mismatch between bass unit and Quad - that's one major reason why commercial subwoofers never blend in with ESL-63s. I tackled this problem by designing a second-order high pass filter with a little response peaking. This equalises the Quad's response, making it flat. The filter also acts to remove low bass which in turn improves the ESL-63's power handling. It keeps the internal audio step-up transformer away from core saturation, a mechanism Quad use to limit low frequency power to the



Quad ESL63 low frequency response and conventional subwoofer response (dotted line). They are impossible to combine perfectly.

speaker. The effect of the filter is, as the response shows, to give the ESL-63 a flat frequency response down to 180Hz or so, below which a -12dB/octave attenuation of low frequencies comes into play.

Rolling off the Quad at 180Hz prevents it from trying to handle low bass, which is a good thing. However, male vocals contain strong energy down to 80Hz. So any subwoofer used will, on occasion, have to handle vocal information - a potential problem. The Celestions did occasionally add a little colouration to deep male vocals. One way of minimising this effect is to use a subwoofer drive unit that is inherently



less coloured, always bearing in mind that the cone must be heavy if it is to have the low free air resonance needed for open-baffle working.

In the overall scheme of things, I didn't feel that occasional "chestiness" was anything more than a minor blemish in this set-up. But I've always accepted that the SL-6000s were far from perfect and needed development. Their prime role here is to demonstrate and confirm the merits of the open baffle dipole subwoofer.

### Celestion SL-6000

Matching the Celestions to the Quads was even more problematical. Talking about colouration, Celestion would surely point out that the SL-6000s were not designed to work up to 180Hz, so what could I expect? Like most subwoofers, their own low pass crossover limits them to 100Hz, a sensible upper limit where true bass gives way to low-midrange, but not one that suits the ESL-63s, for reasons explained. This was less of a concern to me, however, than the complex matter of subjective "speed". Necessarily, to obtain a low free air resonance, the SL-6000s have heavy cones. I believe they were designed as guitar speakers, with heavy paper cones, a long throw and high power handling. Matching them in to the gossamer film of an electrostatic seemed as likely to work as perpetual motion.

Initially, I reasoned that these speakers could best be controlled by the use of motional feedback. Hah! That was false confidence. It took little more than a busy Saturday to find that a simple set-up is inherently unstable and liable to violent antics. Motional feedback senses cone movement and applies correction in a similar fashion to negative feedback. I wound a sensing coil onto the exposed front of an SL-6000's driver voice coil

former to derive a motion related signal.

This experiment was instructive, as well as dramatic. Instability was caused, Graham Bank of Celestion told me, by lack of a position reference. The result was an enormous crack from the cone as it attempted to leave the chassis on music peaks. Each time it did this the connecting braids carrying the signal from frame to voice coil broke, even though they were long enough to cope with the movement. It appeared they fractured under the enormous acceleration involved. Both Graham Bank at Celestion and Paul Mills at Tannoy have worked on motional feedback and between them convinced me that there were some deep seated difficulties in its application, explaining Philips' rapid withdrawal from the field back in the Seventies.

I noted then, in a demonstration at their headquarters in Eindhoven, Holland, that motional feedback gave the sort of fast, tight and even bass most enthusiasts dream about. That's just what I heard too from my own basic version: fantastic bass quality, provided I kept volume down, otherwise, the driver instantly destroyed itself!

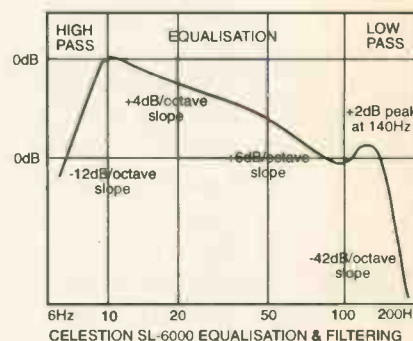
However, my interest was, literally, academic. Analysing the (output) cone velocity signal against electrical input I found, not unexpectedly, that a lot of correction was being applied above 100Hz.

## 2) SUBWOOFER EQUALISATION

Similar correction could be applied passively by the use of equalisation in the low pass crossover network feeding the subwoofer and this is the reason for the peculiarly sharp response peaking above 100Hz you can see in the low-pass subwoofer feed. It injects high frequency energy (as far as bass frequencies go, that is) into the driver to add subjective "speed". Bear in mind that you don't hear this peak as such, because the drive unit cannot accurately reproduce it. It simply injects a little more energy where it is needed and is adjusted subjectively. I found +2dB or so about right for the Celestion drive units, but others may need more or less, according to their

abilities.

Another "speed" injection came from cutting out really low sub-bass frequencies. They contain a lot of energy and decay slowly in the room. This



serves to give an impressive amount of physical presence to sound, but subjectively it weighs it down with lingering room boom. Believe it or not, the Celestion's go too low with the crossover supplied, which has no useful lower limit. My crossover applies tailored bass correction, with less emphasis on lower frequencies (i.e. around 40Hz), which compensates for room gain. It also incorporates a second-order (-12dB/octave) high pass filter at 10Hz to prevent record warps in particular overworking the system.

What you have to bear in mind is that the woofer cones are acoustically undamped and will flap around like crazy if given a chance. The high pass filter acts to limit cone excursion, necessary with this sort of sub-woofer. I managed to get adequately high sound pressure levels out of the SL-6000s though, although they will bottom if pushed too hard when strong subsonics are present.

Bass quality from these speakers varied considerably according to the power amplifier used to drive them; the SL-6000s were quite obviously a severe load. Trying to steady them by hand whilst working was impossible. They draw and reproduce quite staggering amounts of bass energy, shuddering in use, even though heavy and spiked to the floor. This vividly demonstrates just how much acoustic energy an open dipole subwoofer dissipates, although much of it is lost through cancellation.

The 120Hz peak equalisation applied to the SL-6000s is unique to them.

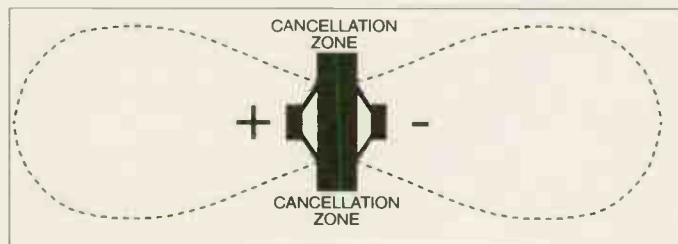
Experimenters interested in this subject could use any large bass unit on an open baffle, or two in parallel to handle the power, and tune out the peak. Just bear in mind that the drivers must be big enough to move a lot of air. A fair amount of experiment will probably be necessary to get the bass sounding right, but a delight of the system is that it's amenable to tweaking. There's no driver/cabinet interaction to contend with, an overriding influence upon the sound of conventional cabinet loudspeakers. This makes the open-dipole subwoofer something of an experimenter's dream, but by now you may well be realising that they also have their problems and peculiarities - and in this section I haven't even talked about the need to tune them into a room. That's even more fun!

## 3) ROOM ALIGNMENT

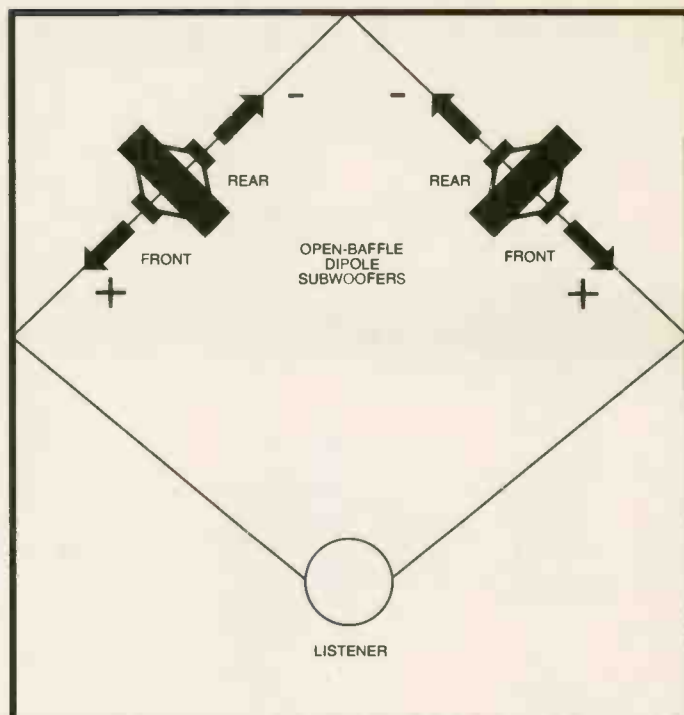
There's one other big, big consideration which rarely gets talked about: tuning into the room. This is a peculiar process unique to the open baffle when it is used to deliver bass. It must be positioned and aligned correctly if it is to produce smooth bass, otherwise it will boom. In the few dipole speakers we have come across, including the Quad ESL-63, this subject is not even raised, let alone discussed, possibly because it is difficult to understand and resolve at a practical level.

Celestion decided to run room analyses on a computer for their customers to solve the problem. We tried to reach an empirical

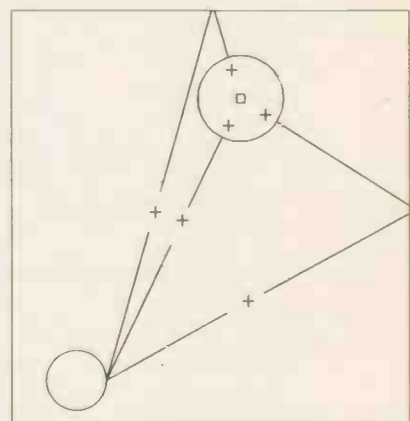
understanding with our SL-6000s, finding only that in all the rooms in which we tried them they had to face outward for best results. The same should apply to Quads, by the way; they should give smoothest bass when facing outward, although I've never tried this. I suspect part of the reason why Quads give peculiar bass is because they are a non-optimally aligned dipole, facing inward to fire high frequencies toward a listener. Experimenters can, of course, easily move an open baffle for best results. Just bear in mind that this is a necessary part of running a dipole bass unit.



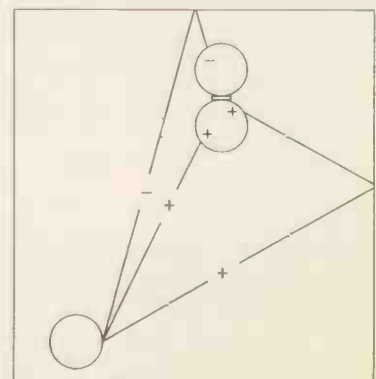
▲ A dipole radiates sound equally from front and rear, but 180 degrees out of phase. Where front and rear wave meet they cancel. This produces a 'dead' zone either side of the speaker. Both Quad and Celestion loudspeakers exhibit this characteristic.



Within all the rooms in which we have used the Celestion SL-6000 subwoofers, best results were achieved with this orientation. We believe the rear wave reverses in phase and cancels at the opposing loudspeaker. While the front wave is heard by the listener the cancellation zones suppress diagonal room modes.



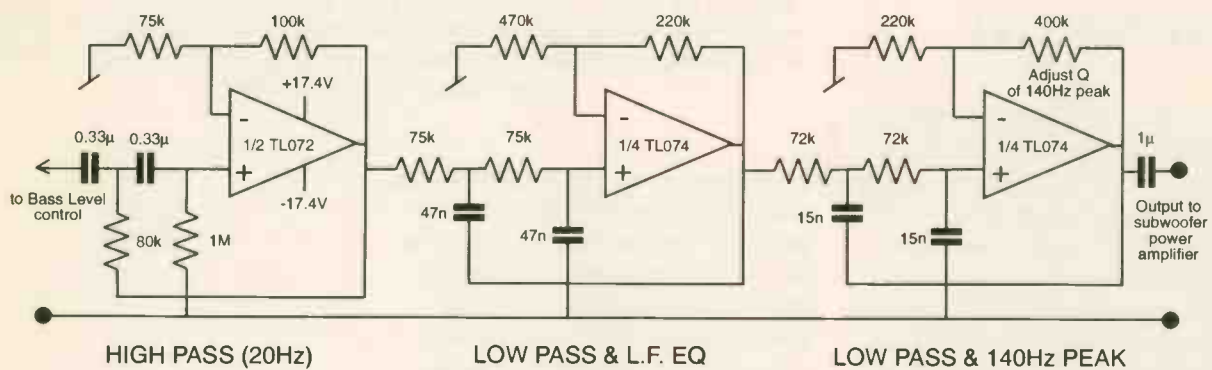
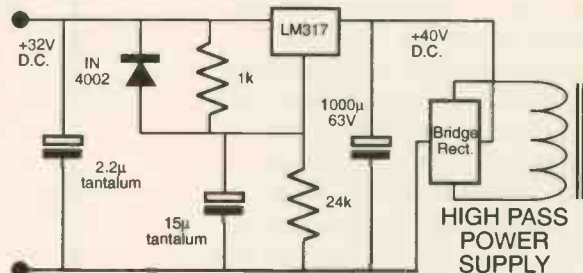
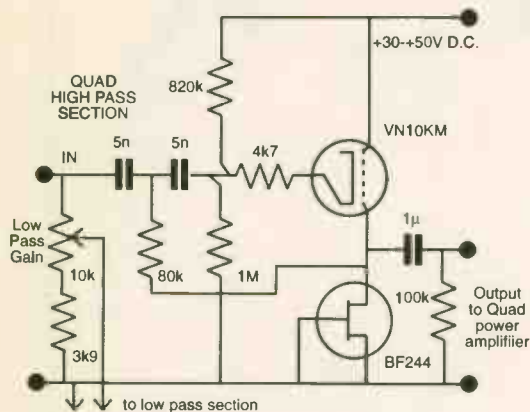
▲ A conventional monopole generates additive reflections off all walls. Their strength and phase depends upon speaker position. The result is unpredictable emphasis.



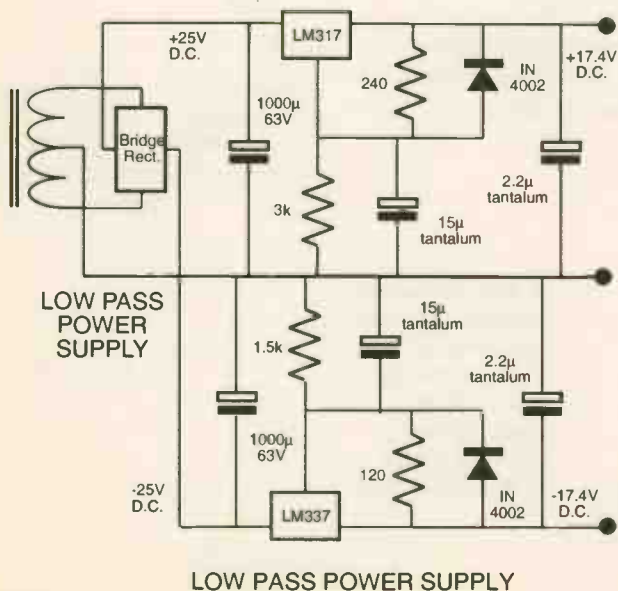
► A dipole can provide negative reflections and, properly arranged, this can be used to give a more balanced overall result in a reflective field like a room.



# CROSSOVER CIRCUITS



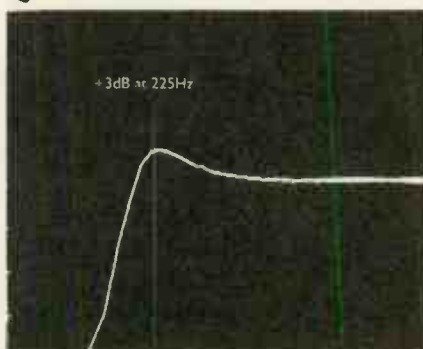
CELESTION SUBWOOFER LOW PASS SECTION



LOW PASS POWER SUPPLY



## QUAD HIGH PASS SECTION



Most filters these days are, knocked up around a silicon chip. It's a fast and easy way of doing things, but not necessarily a satisfactory one. Cheap chips invariably have a sonic signature, something I wanted to avoid in the critical high pass section feeding the Quad. There are innumerable ways of designing such a circuit, but my notional ideal was to use just one high quality amplifying device.

I found that a remarkably high transconductance MOSFET, the VN10KM, offered what I wanted. This thing is a bit of a wonder for audio work, even if it is a pig to use, being almost 'naturally' unstable because of the gain available; a grid stopper must always be used if it is not to oscillate.

In the configuration used here as an active filter, the circuit has an overall gain of one, minimal noise, a very high

overload ceiling and negligible distortion at all frequencies and levels. It also has a high input impedance and a reasonably low output impedance, able to drive down to a  $4k7\Omega$  load with 1000pF in parallel. I measured a 124dB dynamic range. Quad enthusiasts can rest assured that this device is as transparent as one might hope, unlike chip-based filters.

Frequency response can be seen in our explanatory diagram and as an analysis from our spectrum analyser. A -12dB/octave high pass attenuation characteristic serves to prevent bass reaching the Quad, whilst the gentle lift that reaches +3dB maximum at 225Hz equalises the Quad's natural roll-off, giving it a fuller, richer and more balanced sound.

## CELESTION LOW PASS SECTION



Because of the amount of filtering involved here, and the fact that a high level of transparency is not required for heavy bass cones, I used a set of TL072/4 silicon chips for the low pass section.

The circuit is a pretty straightforward arrangement with a second-order high-pass at 10Hz, followed by two cascaded second-order sections that combine to give equalisation and a fast, fourth-order, low-pass roll-off at 150Hz that can be tweaked to yield that vital 140Hz peak. Our diagram and spectrum analysis clearly show what this circuit provides.

Basically, an open baffle needs +6dB /octave bass lift to correct acoustic cancellation. However, room gain due to resonances, usually around the 40Hz-70Hz, must be taken into account, or over-heavy bass results I found. This is a benefit, because low frequency gain can be lessened. It needs to be kept in check if power handling is to be acceptable, and that's why I also included a second-order high pass filter.

I'd suggest you don't get too involved in the filter electronics, as so many engineers do. It is not necessary to use Butterworth responses, for example, in the face of massive imperfections elsewhere. This whole speaker is in fact a struggle to understand and tame various acoustic phenomena of some magnitude; pedantic electronic details are a distraction.

The bass low pass section feeds a power amplifier that in turn drives the SL-6000 subwoofers (or equivalent). This needs to be able to deliver a good 100watts. There are plenty of solid-state amps available second-hand for this purpose, or you could buy an NAD power amp new. They are very good value.

Remember that an open-baffle dipole subwoofer can produce enough bass to shake a building - but cones and power amps are put under severe strain if asked to do so.

In the next DIY Supplement we hope to have our own replacement for the SL6000s up and running, as well as a circuit board for active the crossover ●

Our thanks to Hi-Fi Experience Tel: 0171 580 3535, for the loan of Quad ESL-63s featured in the front cover photograph (ours don't look so smart without their grilles etc.)