Small Signal Audio Design

Second Edition

Douglas Self

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Small Signal Audio Design

This much expanded second edition of ***Small Signal Audio Design*** is the essential and unique guide to the design of high-quality analogue circuitry for preamplifiers, mixing consoles, and many other signal-processing devices. You will learn to use inexpensive and readily available parts to obtain state-of-the-art performance in all the vital parameters of noise, distortion, crosstalk, etc. This practical handbook provides an extensive repertoire of circuit blocks from which almost any type of audio system can be built.

Essential points of theory that determine practical performance are lucidly and thoroughly explained, with the mathematics at an absolute minimum. Virtually every page reveals nuggets of specialized knowledge not found elsewhere. Douglas' background in design for manufacture ensures he keeps a wary eye on the cost of things.

Learn how to:

- Make amplifiers with apparently impossibly low noise
- Design discrete circuitry that can handle enormous signals with vanishingly low distortion
- Use ordinary bipolar transistors to make amplifiers with an input impedance of more than 50 Megohms
- Transform the performance of low-cost-opamps, and how to make filters with very low noise and distortion
- Make incredibly accurate volume controls
- Make a huge variety of audio equalisers
- Make magnetic cartridge preamplifiers that have noise so low it is limited by basic physics
- Sum, switch, clip, compress, and route audio signals effectively
- Build reliable power-supplies, with many practical ways to keep both the noise and the cost down

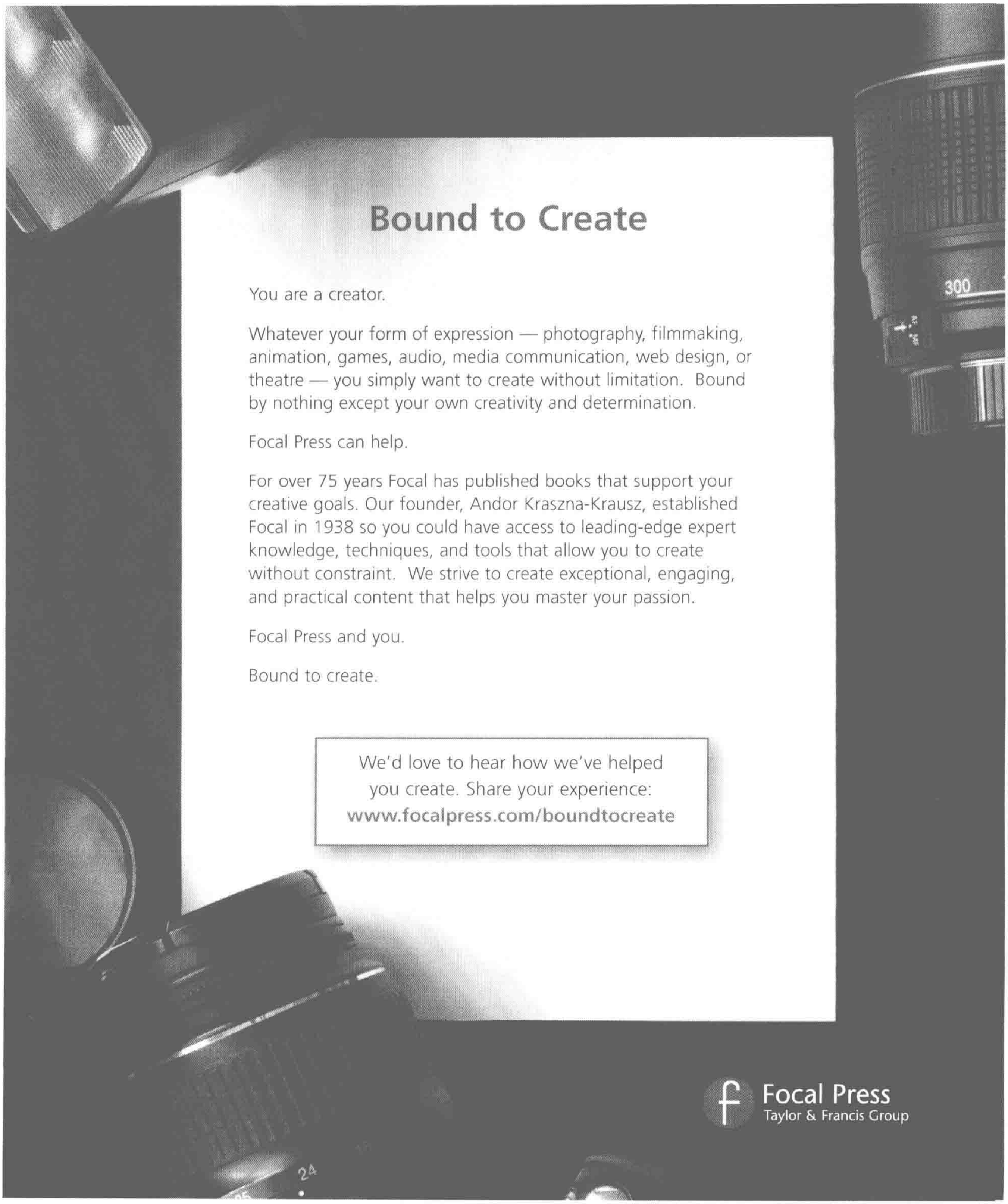
This much enlarged second edition is packed with new information, including completely new chapters on:

- Opamps for low voltages (down to 3.3 V)
- Moving-magnet inputs: archival and non-standard equalisation, for 78s etc.
- Moving-magnet inputs: discrete transistor circuitry
- Moving-magnet inputs: noise and distortion
- Balance and width controls
- Headphone amplifiers, including Class-A designs

There is also new material on: using multiple components to improve accuracy, ultra-linear discrete opamps, RIAA optimisation, the Baxandall volume control, distributed volume controls, loudness controls, the ideal balance-control law, instrumentation amplifier inputs, ground-cancelling outputs, zero-impedance outputs, and system control by microcontrollers.

This book includes numerous circuit blocks with component values so you can build them at once and easily adapt them to your particular requirements. It is lavishly illustrated with diagrams and graphs, and full of practical measurements on real circuitry using state-of-art testgear.

Douglas Self studied engineering at Cambridge University, then psychoacoustics at Sussex University. He has spent many years working at the top level of design in both the professional audio and hifi industries, and has taken out a number of patents in the field of audio technology. He currently acts as a consultant engineer in the field of audio design.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Dedication

To Julie, with all my love

Preface

Scientia potentia est

'Another damned thick book! Always scribble, scribble, scribble! Eh, Mr. Gibbon?'

Attributed to Prince William Henry, Duke of Gloucester, in 1781 upon receiving the second volume of *The History of the Decline and Fall of the Roman Empire* from its author.

This book deals with small-signal audio design; the amplification and control of audio in the analogue domain, where the processing is done with opamps or discrete transistors, usually working at a nominal level of a volt or less. It constitutes a major update of the first edition, being some 50% longer. 'Small-signal design' is the opposite term to the 'large-signal design' which in audio represents power amplifiers driving loudspeakers, rather than the electricity distribution grid or lightning.

There is unquestionably a need for high-quality analogue circuitry. For example, a good microphone preamplifier needs a gain range from 0 to +80 dB if it is to get any signal it is likely to encounter up to a workable nominal value. There is clearly little prospect of ever being able to connect an A-to-D converter directly to a microphone. The same applies to other low-output transducers such as moving-coil and moving-magnet phono cartridges. If you are starting at line level, and all you need is a simple but high-quality tone control, there is little incentive to convert to digital via a relatively expensive ADC, perform the very straightforward arithmetic manipulations in the digital domain, then go back to analogue via a DAC; there is also the need to implement the actual controls as rotary encoders and have those overseen by a microcontroller. All digital processing involves some delay, because it takes time to do the calculations; this is called the latency and can cause serious problems if more than one signal path is involved.

The total flexibility of digital signal processing certainly allows greater scope – you might contemplate how to go about implementing a one-second delay in the analogue domain, for example – but there are many times when greater quality or greater economy can be obtained by keeping the signal analogue. Sometimes analogue circuitry connects to the digital world, and so a complete chapter of this book deals with the subtleties of analogue/digital interfacing.

Therefore analogue circuitry is often the way to go. This book describes how to achieve high performance without spending a lot of money. As was remarked in a review of my recent book *Active Crossover Design*, duplicating this performance in the digital domain is not at all a trivial business. You can, of course, start off in analogue, and when you have identified the filter slopes, equalisation curves, and what-not that you want it is relatively easy to move it over to the DSP world.

I have devoted the first few chapters to the principles of high-quality, small-signal design, moving on to look closely at first hifi preamplifiers, and then mixing consoles. These two genres were chosen partly because they are of wide interest in themselves, but also because they use a large number of different functional blocks, with very little overlap between them. They cover a wide range of circuit functions that will be useful for all kinds of audio systems. You will find out how to adapt or design these building-blocks for audio, and how to put them together to form a system without bad things happening due to loading or interaction. You should then be able to design pretty much anything in this field.

In the pursuit of high quality at low cost, there are certain principles that pervade this book. Low-impedance design reduces the effects of Johnson noise and current noise without making voltage noise worse; the only downside is that low impedance requires an opamp capable of driving it effectively, and sometimes more than one. The most ambitious application of this approach so far has been in the ultra-low noise Elektor 2012 Preamplifier.

Another principle is that of using multiple components to reduce the effects of random noise. This may be electrical noise, in which case the outputs of several amplifiers are averaged (very simply, with a few resistors) and the noise from them is partially cancelled. Multiple amplifiers are also very useful for driving the low impedances just mentioned. Alternatively, it may be numerical noise, such as tolerances in a component value – making up the required value with multiple parts in series or parallel also makes errors partially cancel. This technique has its limits because of the square-root way it works; four amplifiers or components are required to half the noise, sixteen to reduce it to a quarter and so on.

There is also the principle of 'optimisation', in which each circuit block is closely scrutinised to see if it is possible to improve it by a bit more thinking. One example is the optimisation of RIAA equalisation networks. There are four ways to connect resistors and capacitors to make an RIAA network, and I have shown that one of them requires smaller values of expensive precision capacitors than the others. This new finding is presented in detail in Chapter 8, along with related techniques of optimising resistor values to get convenient capacitor values.

In many places, hybrid amplifiers combining the virtues of discrete active devices and opamps are used. If you put a bipolar transistor before an opamp, you get lower noise but the loop gain of the opamp means the distortion is as good as the opamp alone. This is extremely useful for making microphone amplifiers and virtual-earth summing amplifiers. If you reverse the order, with an opamp followed by bipolar transistors, you can drive much heavier loads, with the opamp gain once again providing excellent linearity. This latter technology, among others, is explained in a brand new chapter on headphone amplifiers.

So much has been added that it is difficult to summarise it, but the new material includes:

- An increasing demand for 5 V and 3.3 V single-rail audio with good performance has led to a whole new chapter on low-voltage opamps. Likewise there is new information on analogue switching with low supply rails.
- The material on moving-magnet and moving-coil amplifiers has been much expanded to include non-standard replay equalisation (for 78s, wax cylinders, etc.), more on moving-magnet noise, the ultimate limits on moving-coil noise performance, specialised filtering, and more. Mind you, the fact that it needs four whole chapters to cover the process of extracting a reasonable signal from a record groove indicates to me that there is something amiss with the whole concept.
- There is much more on discrete transistor circuitry, especially input stages for moving-magnet cartridges, and discrete opamps with ultra-low distortion.
- Active volume controls, especially the Baxandall control, are covered in greater depth. Loudness controls are currently unfashionable but the thinking behind them is intriguing. I include a possible solution to the mystery of why almost everyone disliked them, when consensus of any sort is rare in the hifi business.
- Balance controls now have their own chapter: passive, active, and switched types are covered, plus the technology for true constant-volume balance systems.
- The tone-control chapter is much expanded, and includes my new split-drive configuration which makes it practical to use 1 kΩ pots in a low-impedance design, giving much lower noise. There is a new design that gives variable-frequency HF and LF control in one stage, and a new type of switched-frequency LF EQ.
- Instrumentation amplifiers have long been praised for giving good common-mode rejection, but this has been hard to exploit in audio. I demonstrate how to do it, and get improved noise at the same time.
- There is much more on the ingenious but little-known technology of ground-cancelling outputs, showing how they can give a noise advantage over conventional balanced interconnections. Cunning ways of substantially reducing line output transformer distortion at near-zero cost are described.
- One of the many new chapters is devoted to headphone amplifiers, including hybrid types and a discrete Class-A design with ultra-low distortion.

- In the field of mixing console design, there is more on routing systems, balanced virtual-earth summing amplifiers, and level indication, including the Log Law Level LED or LLLL, which gives much more level information from a single LED than just on/off.
- The chapter on interfacing with the digital domain now includes the use of housekeeping microcontrollers for muting, input selection, IR decoding, and so on.

However, what you most emphatically will *not* find here is any truck with the religious dogma of audio subjectivism – the directional cables, the oxygen-free copper, the World War One vintage triodes still spattered with the mud of the Somme, and all the other depressing paraphernalia of pseudo- and anti-science. I have spent more time than I care to contemplate in double-blind listening tests – properly conducted ones, with rigorous statistical analysis – and every time the answer was that if you couldn't measure it you couldn't hear it. Very often if you could measure it you still couldn't hear it. However, faith-based audio is not going away any time soon because few people (apart, of course, from the unfortunate customers) have any interest in it so doing; you can bet your bottom diode on that. If you want to know more about my experiences and reasoning in this area, there is a full discussion in my book *Audio Power Amplifier Design.*

A good deal of thought and experiment has gone into this book, and I dare to hope that I have moved analogue audio design a bit further forward. I hope you find it useful. I hope you enjoy it too.

All suggestions for the improvement of this book that do not involve its combustion will be gratefully received. My email address can be found on the front page of my website at www.douglas-self.com.

To the best of my knowledge no supernatural assistance was received in the making of this book.

Further information, and PCBs, kits and built circuit boards of some of the designs described here, such as phono input stages and complete preamplifiers, can be found at www.signaltransfer.freeuk.com

Douglas Self

London, December 2013

Acknowledgments

My heartfelt thanks go to

Gareth Connor of *The Signal Transfer Company* for unfailing encouragement, providing the facilities with which some of the experiments in this book were carried out, and with much appreciation of our long collaboration in the field of audio.

Acronyms

ADC	Analog-to-digital converter
AFL	After-fade listen
AGS	Active gain stage
BFMA	Balanced-feedback microphone amplifier
BJT	Bipolar junction transistor
CFA	Current feedback amplifier
CFP	Complementary feedback pair
CM	Common mode
CMOS	Complementary metal oxide semiconductor
CMRR	Common-mode rejection ratio
CRM	Control-room monitor
DAC	Digital-to-analog converter
EF	Emitter-follower
EIN	Equivalent input noise
EQ	Equalization
ESR	Equivalent series resistance
ETP	Electrolytic tough pitch
FET	Field-effect transistor
FS	Full scale
GC	Ground canceling
HF	High frequency
IC	Integrated circuit
IDC	Insulation-displacement connector
JFET	Junction field-effect transistor
LED	Light-emitting diode
LF	Low frequency
MC	Moving-coil
MM	Moving-magnet
MOSFET	Metal oxide semiconductor field-effect transistor
NF	Noise figure
NFB	Negative feedback
OTA	Operational transconductance amplifier
PA	Public address
PCB	Printed-circuit board
PFL	Prefade listen
PGA	Programmable gain amplifier
PPM	Peak programme meter
PSRR	Power-supply rejection ratio
RF	Radio frequency
RIAA	Recording Industry Association of America
RTF	Return to flat
SIP	Solo in place
SM	Surface mount
TH	Through hole
THD	Total harmonic distortion
VAS	Voltage-amplifier stage
VCA	Voltage-controlled amplifier
VCVS	Voltage-controlled voltage source

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