Analogue electronics on the other hand, had, and still has, good ROM (*read-only memory*) in the form of *gramophone records* and *electronically programmable memory* (EPROM) in the form of *magnetic tape*. Both technologies in fact offer some ability to be accessed randomly and tape-loops, speed-manipulation, editing, "scrubbing" and "scratching" techniques – all developed with analogue media – still represent some of the most important musical concepts developed in the twentieth century. This would be reason enough to cover them in this book. But, strikingly, analogue media still retain a fascination with younger musicians and engineers, so a whole chapter is devoted to them here.

Gramophone records (78s and LPs)

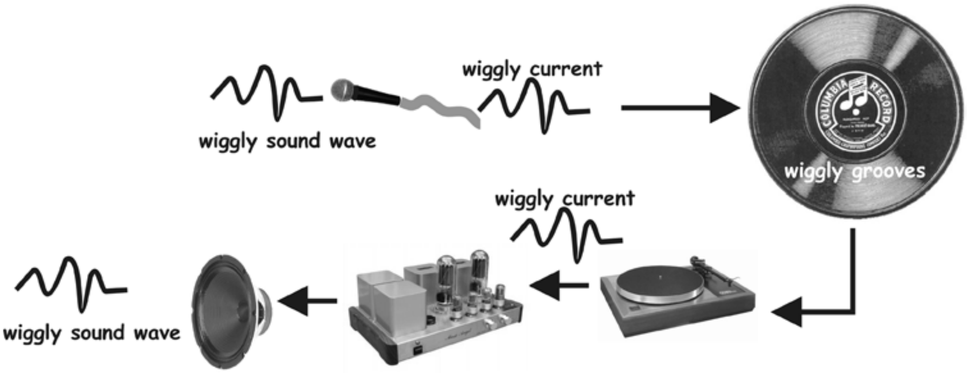

Figure 1 - Analogue recording and replay system – it's all about wiggles!

A gramophone record (called a *phonograph record* in the USA) is an analogue sound storage medium in which a flat disc of material is impressed with two sound-bearing concentric spiral grooves, one on each side of the disc; running from the outside edge of the disc towards the centre. As the original, completely smooth, *lacquer* disc turns, sound signals are engraved as modulations ("wiggles", see Figure 1) in a spiral groove. On replay, a needle (or *stylus*) traces these modulations in a manufactured copy of the lacquer disc.

Figure 2 - An early gramophone

In early acoustic gramophones (the reproduction device), these modulations were converted directly to sound by coupling the stylus to a diaphragm at the throat of a horn which amplified the signal acoustically (Figure 2). However, since the nineteen-thirties, both the recording and reproduction of gramophone records have been electronic; although originally they were called *electric recordings*. In the electronic gramophone system, analogue signals from microphones, or from tape, are amplified and drive a powerful disc-cutter which cuts the original lacquer disc on a specially adapted lathe. When the record is replayed, the stylus traces the grooves and is arranged to move a small magnet near a coil[2], the whole assembly being termed a *moving-magnet pickup cartridge* (Figure 3). A very small voltage is thus generated which is subsequently amplified and used to drive a loudspeaker.

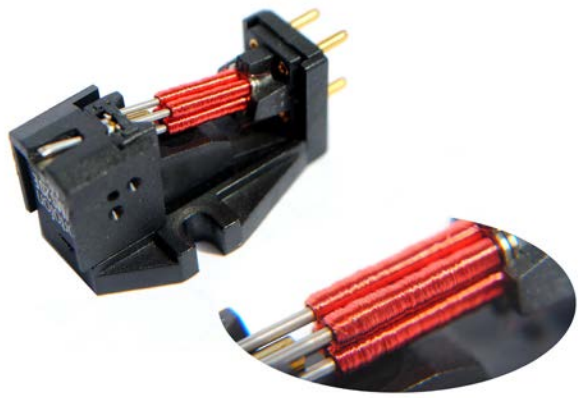

Figure 3 - The internals of a moving magnet cartridge

Gramophone records are usually catalogued according to their (roughly standard) diameters of “12 inch”, “10 inch”, and “7 inch”, Early records were made of a mix of shellac, powdered slate and a filler derived from cotton. These discs were recorded and replayed at 75 to 80 RPM (revolutions per minute) and are now universally referred to as “*78s*”. Due to the high rotational speed, these early discs only played for a few minutes and were plagued by high surface-noise as the stylus traced the granular nature of the recording medium.

A huge step in quality was made in 1948 with the introduction of the long-playing (LP) record by Columbia Records. Turning at 33⅓ RPM and manufactured from a smooth plastic material (PVC, blackened with carbon), these discs transformed the sound-quality available from the medium, increasing playing-time to about 20 minutes a side, and drastically cutting surface-noise.

Although, unquestionably, the most important technical advance in the history of recorded sound, the LP record left a cultural hole where the “78” had once been. So significant had the earlier medium been on cultural taste and consumption that it is a reasonable conjecture that the history of popular music, and the development of the pop-song was due to the limited recording time and limited dynamic-range of the “78” disc. Whilst the LP record re-invigorated classical music sales and *albums* or collections of songs from popular artists, there remained the need to re-invent a medium for the *three-minute song*. The industry’s response was the seven-inch, 45 RPM *single*, manufactured either with vinyl, or more commonly in polystyrene and introduced by RCA Victor in 1949.

[2] Although there exist much rarer pickup cartridges in which a coil is contrived to move in a magnetic field, this being called a moving-coil cartridge, and further - "cheap and cheerful" - cartridges based on *piezo-electric* principles.

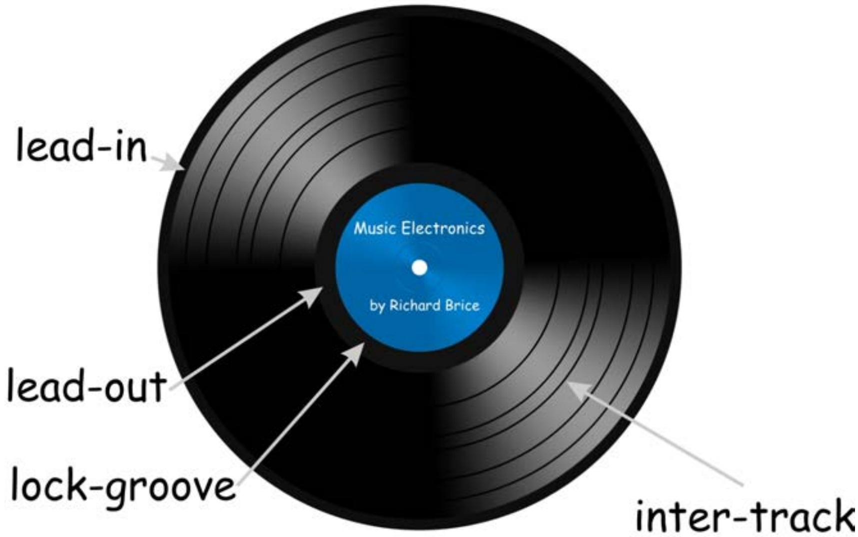

Figure 4 – Structure of the spiral track on one side of an LP record

A typical (300mm or “12-inch”) LP record is illustrated in Fig. 4. The spiral groove runs from the outside of the record to the inside, but the diameter of the spiral does not decrease linearly across the diameter. At the outer edge of the disc a small portion of the diameter (about 6mm) is devoted to a section called the *lead-in*, where the groove is widely spaced and silent. And between the separate songs or sections (*tracks*) on the recorded section of the spiral-groove, a short gap of around 1 mm is arranged where, once again, the groove is widely spaced. Both the lead-in and the *inter-track spaces* are clearly visible, the idea being that the stylus may be lowered onto the lead-in or the inter-track to avoid damaging the recorded section of the groove when playing the entire disc or selecting a particular track. Towards the centre of the record, at the end of the groove, another wide-pitched section of spiral is arranged known as the *lead-out*. At the very end of this section, the last part of the spiral meets an earlier part to form a circle called the *lock-groove*. When the stylus reaches the lock-groove, it will circle repeatedly until it is lifted from the record.

Mechanical limitations

Being an entirely mechanical device, gramophone records suffer from a number of mechanical problems and limitations.

Wow and rumble

Perfect reproduction would require both the recording lathe and the gramophone player (*record decks*) to turn at precisely the same speed and with no short-term variations - these being known by the onomatopoeic term for pitch-instability; *wow*. In practice, a very high performance is achieved in this regard from modern, high-quality decks by using high-quality electric motors, often controlled with crystal oscillators.

Mechanical vibration from the driving motor (both in the lathe and the reproducer) must also be mechanically isolated from the turntable on which the record sits. A number of mechanical arrangements are used, the simplest being to mount the driving motor solidly in the turntable plinth and suspend the turntable and tone-arm on an acoustically separate *sub-chassis* - isolated with springs and dampers from the main plinth. The drive from the motor is communicated to the turntable via a compliant (elasticised rubber) belt; thereby decoupling any motor vibration above a very low frequency. One final source of noise is the turntable bearing which must possess a very high degree of surface-finish if vibration from the bearing isn’t to be transduced by the pickup, an effect termed *rumble*. Modern lathes and high-quality record reproducers all offer a very high performance in all these areas; although the same cannot be said for many players during the heyday of gramophone records!

Falling wavelengths

The choice of a constant rotational speed for gramophone records, whether 78, 45 or 33⅓ RPM, ensures simple and convenient mechanics, but it follows that as the disc is cut and replayed, the wavelengths fall throughout the duration of the recording (because the diameter of the spiral at centre of the disc is about 1/3rd of the spiral at the outside grooves). Due to this, the quality of gramophone records falls throughout the duration of the recording so that harmonic distortion is often apparent on heavily modulated programme towards the centre of the disc.

Figure 5 - The Linn Sondek, a famous high-end record-player incorporating a suspended, mechanically and acoustically isolated sub-chassis for the tone-arm and turntable and belt drive from an (optionally) crystal-controlled high-quality motor. The turntable is supported on a single-point bearing for minimum *rumble*.

Tone-arm tracking

In the recording process, the cutter chisel is moved on a parallel bar across the disc radius (see Fig. 6). Ideally, a reproducer would track along a radius in order to maintain the stylus a right-angles to the groove. This may only be achieved by a parallel guide support, whereas, in a normal record deck, the stylus and pickup are mounted at the end of a long tone-arm which pivots around a point. The pickup thereby traces an arc - rather than a radius - across the record surface. Obviously, the longer the tone-arm, the nearer the arc may be made to resemble a radius, but - in practice - this would result in an impractically long tone-arm. A reasonably good performance is obtained in modern tone-arms by cranking the pickup head in relation to the axis of the tone-arm and in arranging the stylus point to pass in front of the turntable centre (see Figure 7). By this means, a compromise is struck so that the error angle between the axis of the pickup stylus and the groove tangent is reduced to plus/minus a few degrees across the recorded groove.

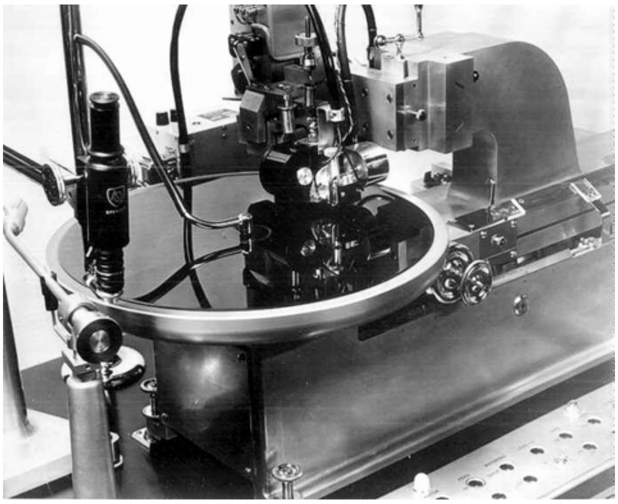

Figure 6 - Disk lathe showing how the cutter chisel is moved on a parallel bar across the disc radius

Figure 7 - By cranking the pickup head in relation to the axis of the tone-arm and in arranging the stylus point to pass in front of the turntable centre the pickup stylus and the groove tangent is reduced to plus/minus a few degrees across the recorded groove.

Dust and scratches

The plastic material from which LPs and singles are fabricated, combined with the friction of the stylus, results in the build up of electric charge which attracts dust particles into the recorded groove. These create “clicks and pops" as the replay stylus encounters them and is forced to move around or over them. Careful cleaning of records is therefore essential to the best possible quality. Great care must also be taken of gramophone records, since the recorded medium is relatively soft and may be scratched and damaged by mishandling.

Equalisation

Due to mechanical considerations, the signal recorded onto a vinyl record is pre-equalised, whereby the bass is cut and the treble boosted during the cutting of the master disk. If this isn’t done, the big “wiggles” of the musical bass frequencies tend to throw the needle out of the groove on playback, or break through to an earlier rotation of the spiral groove in cutting. Additionally, by boosting the treble, a better overall noise performance is secured. Replay electronics is therefore required to present a complimentary characteristic. At the start of the LP-era, various equalisation characteristics were defined. However the characteristic defined by the Recording Industries Association of America is now universally adopted, and the replay circuit is always dubbed the *RIAA preamplifier*.

The transfer function of the pre-equalisation applied to the disk-cutter is given by the transfer function,

$$\mathbf{H(j\omega) = [(1 + j\omega\, \mathit{T1})\, (1 + j\omega\, \mathit{T3})] / (1 + j\omega\, \mathit{T2})} \quad \textbf{......... (A)}$$

where ***T1* = 3180µS**, ***T2* = 318µS** and ***T3* = 75µS**. A circuit which gives a close approximation to this characteristic is given in Fig. 8 and may be used to test RIAA equalisation stages.

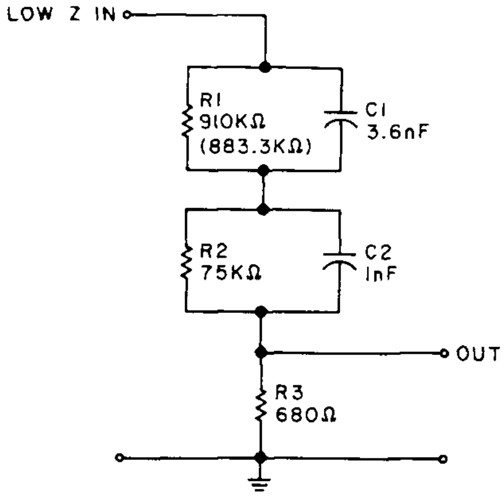

Figure 8 - RIAA encoding network

The complementary, replay characteristic is the inverse of the pre-equalisation transfer function given above. That's to say,

$$\mathbf{H(j\omega) = (1 + j\omega\, \mathit{T2}) / [(1 + j\omega\, \mathit{T1})\, (1 + j\omega\, \mathit{T3})]} \quad \textbf{.......... (B)}$$

Provided the time-constants are the same on the replay side, if we multiply this second equation by the first, all the terms cancel out leaving unity; meaning that the overall encode-decode process is transparent and the reproduced music will retain its original frequency response.

Knowing that the combined effect of multiple filter networks has its mathematical equivalent in the multiplication of individual transfer functions, means we can infer that the correct, combined transfer-function may be synthesised from the combination of two, simple networks with the form,

$$\mathbf{H(j\omega) = 1/(1 + j\omega \mathit{T})}$$

And a third network of the form,

$$\mathbf{H(j\omega) = (1 + j\omega \mathit{T})}.$$

The gain and phase plot of the *replay transfer-function* (B) are plotted in Fig. 9 for reference.

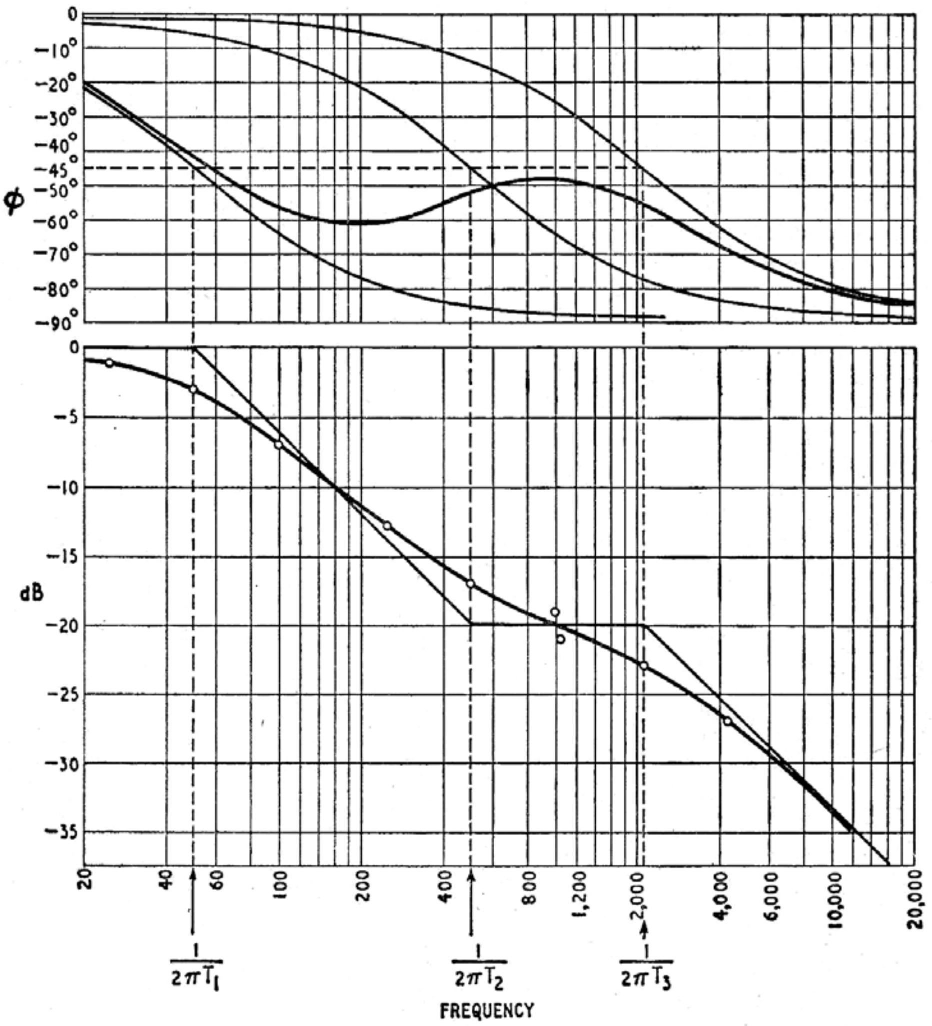

Figure 9 - RIAA replay characteristic indicating amplitude and phase response of the transfer function given in equation B

Here we hit a slight, practical complication. Although, in principle, it would be possible to combine the circuits with simple transfer functions together, in practice the impedances of the various networks interfere with each other unless they are separated by buffer amplifiers to isolate one from the other. Such an approach is certainly feasible. However, it would be complicated and would probably add to the electrical noise generated. Fortunately, there are simple circuits which may be designed to do double-duty. Such a circuit is given in Fig. 10. It is known as a step-circuit or a *shelving-equaliser*. This type of circuit is very widely used in analogue audio.

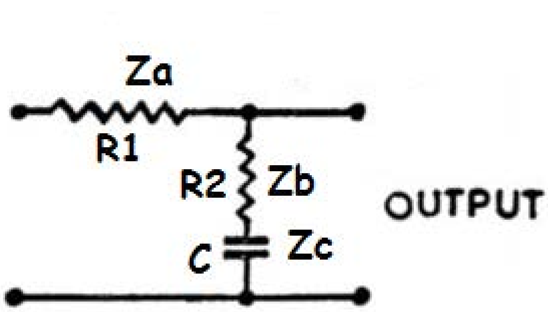

Figure 10 - Step-circuit or a shelving-equaliser