A new displacement-sensitive phono cartridge

A novel design which dispenses with RIAA equalisation

by Richard Brice

In recent years, my approach to archiving vinyl records has been to undertake the necessary RIAA characteristic equalisation in software (see http://pspatialaudio.com/). This entirely digital approach sidesteps limitations in the precision and dynamic-range of analogue equalisation circuits.

But processing unequalised "needle-drop" recordings is clearly useless when you simply want to sit and listen to a record which I still want to be able to do as a fully paid-up member of the vinyl revival. Here I was forced back upon the standard high-gain, three time-constant RIAA equalisation circuit, a conclusion I was loath to accept.

Inspired by my earliest experiences of record players equipped with ceramic pickups which contained no equalisation circuitry, I became interested in displacement-sensitive phono cartridges; based initially upon strain-gauge transducers, or light-valves. These cartridges do not require RIAA equalisation either.

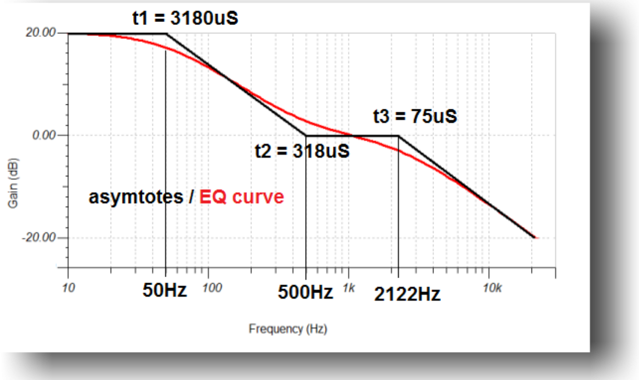
The resulting engineering work has led to the development of an elegant displacement-sensitive phono cartridge which combines excellent mechanical and electrical performance.

Away RIAA!

Why should we want to get rid of the RIAA equalisation?

In effect, an RIAA equaliser is a very powerful tone-control - and those two words alone should send most audiophiles rushing for the smelling-salts!

More seriously, the RIAA tone control is there to mollify a shortcoming of the phono cartridge. It is widely assumed that RIAA replay equalisation is required because the information recorded on a vinyl disc has extensive bass cut and treble boost. But this is not the case. Engraved in the disc's grooves is a substantially constant-amplitude characteristic. The RIAA tone-control predominantly corrects for the velocity sensitivity (or rising frequency response) of the cartridge: not to compensate for the recording characteristic.



The specification of the RIAA tone-control was standardised for all records from 1955: the parameters are illustrated in the graph.

In other words, if we translate the "wiggles" of the record-groove directly into an electrical signal, we don't need equalisation.

And that's exactly what the old ceramic pickups of the past and strain-gauge and optical cartridges do. They don't require the changing position of the stylus to derive a signal. The transduced quantity is thereby not stylus *velocity*, as it is in a moving-coil or moving-magnet cartridge. Instead, the output voltage is a direct measure of the actual record groove contour, or the stylus *displacement*. So, equalisation is not required.

Early experiments

In the strain-gauge phono cartridge, the movement of the stylus directly controls the resistance of a conducting channel by applying pressure to a semiconductor sensor. In considering developing such a transducer, there is the very considerable engineering hurdle to overcome in that the mechanical impedance of the transducing element is several hundred times greater than the permissible stylus-tip impedance. As with ceramic cartridges, the solution is a lever system. But it's a major engineering challenge to design a phono cartridge in which the stylus ultimately pushes and pulls upon a mass. I'm not a mechanical engineer, so I therefore ruled-out experimenting with this type.

The optical approach seemed to offer more scope in that the mechanical task appeared more straightforward. But my experiments soon revealed that generating a low-distortion, low-noise output signal which is a linear function of stylus displacement is "non-trivial".

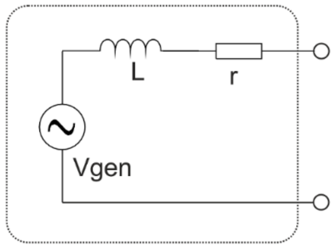
Eureka !

In any case, I realised that a mechanical solution was not required. Instead, an electronic solution was available, and here I felt I was on much safer ground as it meant I could use the mechanics of a standard cartridge and restrict my work to modifications to the electrical generator (as we shall see).

The essential concept behind the new cartridge is to operate an electrodynamic cartridge as a displacement-sensitive current-generator rather than as velocity-sensitive voltage-generator; the latter being the normal approach.

A displacement transducer

The figure below illustrates the equivalent circuit of the electrodynamic cartridge in which a voltage generator feeds a complex internal impedance comprising a resistive component (***r***) and an inductive component (***L***)[1].



Normal operation of the electrodynamic cartridge is that the open-circuit voltage is developed across a resistor which is substantially greater in value than the resistive component of the pickup (***r***). It is this voltage signal which is normally amplified by the RIAA preamplifier.

An electrodynamic phono cartridge may be made displacement-sensitive if the short-circuit output-current is sensed, rather than the open-circuit output-voltage. The full (and inevitably somewhat mathematical) reason for this is given in the Appendix. Below is a simplified explanation without recourse to mathematics.

The essential concept behind the new cartridge is to operate an electrodynamic cartridge as a displacement-sensitive current-generator rather than as velocity-sensitive voltage-generator.

Faraday discovered that the voltage generated in a coil of wire in a magnetic field is related to the rate at which the magnetic-flux changes. In a phono cartridge, the changing flux will thus depend on the velocity of the stylus; because it's the stylus' movements, communicated by the cantilever, which alter the magnetic field strength by moving

[1] This is an equivalent-circuit. These components are not discrete and, in a stereo pickup, two such circuits exist.

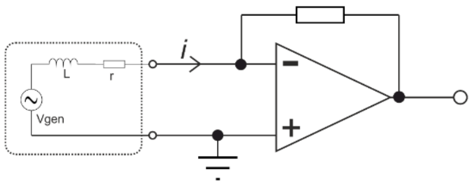
one part of the generator relative to the other[2].

Simply put, the faster the stylus moves, the more voltage is generated.

Now, if this velocity-derived voltage is arranged to flow in the generator coil by shorting the output terminals, an effect called self-inductance creates a voltage in the coil which opposes the generated voltage. This is a manifestation of Lenz's law and the opposing voltage is called a counter-electromotive force or *back-EMF*. This back-EMF is also dependent on the rate at which the current in the coil changes. You could say that it too is velocity-sensitive.

It works like this. The quicker the stylus moves, the greater the generator voltage. But the quicker the current moves in the generator coil (forced as it is to do this by a short-circuit), so the more the back-EMF in the coil opposes the movement of that current. Happily, the two effects exactly cancel-out and the current-term is rendered independent of the rate of change of the displacement of the stylus and is dependent instead on the amplitude of the stylus movement.

Preamplifier



Now, at this point, it would be reasonable to ask: what's the use of a transducer with short-circuited terminals. How do you get the signal out? The circuit above illustrates how this current may be detected and amplified. Here, the cartridge feeds a *trans-resistance* or *trans-impedance* preamplifier. The amplifying action of the amplifier and the feedback resistor hold the inverting input (-) at the same potential as its non-inverting input (+). Because both terminals are forced to the same voltage, the cartridge is fooled into thinking it's working into a short-circuit.

With careful electronic design, the result is a line-level voltage generated at the output of the amplifier stage which is an extremely accurate representation of the groove displacement.

Too good to be true?

Inevitably, in a practical application of this invention there are a few complications to consider.

If a cartridge were constructed with superconducting wire, the cartridge would go on being position-sensitive all the way to 0Hz (DC).

Firstly, the information recorded onto the vinyl record does not have an entirely uniform amplitude characteristic vs. frequency. To limit the velocity of the cutter-head when making the acetate, the high-frequency portion of the signal range is reduced in level in comparison with the lower-frequency. This is the role of the equaliser in the cutting-lathe and the reason for the "dog-leg" in the RIAA characteristic between 500Hz and 2122Hz.

However, the maximum range of equalisation required to return recorded frequencies above 500Hz to the correct level is modest: only *four percent of the degree of equalisation required in the normal RIAA equaliser* circuit. This degree of equalisation may be secured by means of a wide, damped mechanical resonance in the cartridge itself. Or, it may be implemented in the replay electronics.

The second complication arises due to the RIAA recording characteristic which reverts to constant-velocity in the portion of

[2] Magnet relative to coil in a MM type, and coil relative to magnet in a MC type.

the frequency-range below 50Hz (see the graph). The phono cartridge must therefore be returned to velocity operation in the lowest octaves of the frequency-range to compensate for this or the bass reproduction will be overpowering.

Here, the imperfections of real coils made with real wire comes to our rescue. If a cartridge were constructed with superconducting wire, the cartridge would go on being position-sensitive all the way to 0Hz (DC). But real coils possess resistance and this resistance ensures that part of the short-circuit current will always be dependent on stylus velocity. Provided the coils of the cartridge are wound with a specific ratio of inductance to resistance, the cartridge can be made to operate exactly as required. This is further explained in (2) in the Appendix.

Lastly, it's a plausible concern that shorting the generator in a phono cartridge will damp the free movement of the mechanical system. However, if the two systems are arranged to be coupled loosely, there is insignificant damping effect on the mechanical system by the circulating current, see Appendix (3).

DisC and PHATHOM

The Phaedrus Audio **DisC** phono cartridge and **PHATHOM** base-station are commercial realisations of the work described above. The name **DisC** is a contraction of **Dis**placement **C**artridge.

Recovery of the current-mode signal from the cartridge, suitably amplified for connection to a standard preamplifier or integrated amplifier is performed by the **PHATHOM** base-station (the interior of which is illustrated above). The design of this unit is simplified, in that no RIAA equalisation is included. But precision and very low-noise circuit techniques are required as the signal currents involved are very small (nano-amperes).

No modifications are required to turntable or cabling to support a **DisC** phono cartridge. Operating the cartridge in current-mode ensures that the interface is very low impedance which guarantees freedom from crosstalk, capacitive cable effects and noise and hum. Installing the PHATHOM base-station is no more complicated than installing a normal RIAA preamplifier. The milled aluminium body of the **DisC** cartridge is tapped so that it is fixed to the head shell with 2 x M2.5 austenitic stainless-steel bolts on 12.7mm (1/2 inch) centres. This ensures good physical contact and simplifies installation.

The operation of an electrodynamic phono cartridge as a displacement transducer is the subject of patent applications. •

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Appendix

Faraday's law states that the induced EMF in a coil of thin wire is,

$$-E = \frac{d\phi}{dt} \cdot k$$

where ***E*** is the electromotive force, ***ϕ*** is the magnetic flux, and ***k*** is a constant which also incorporates the number of turns in the coil.

In an electrodynamic phono cartridge, the magnetic field is dominated by the proximity of the permanent magnet relative to the coil. So, we can take ***ϕ* = *P***, where ***P*** is the position of the magnet relative to the coil. If we recast Faraday's law in terms of ***P*** (and ignore the direction convention for convenience) we can say,

$$E = \frac{dP}{dt}$$

This equation is the heart of a velocity-sensitive pickup: it is according to this relationship that all MM or MC cartridges operate.

To see what happens when this EMF is forced to circulate in the coil of the cartridge, we can substitute this expression into the current-voltage relationship in an inductor which is,

$$i = \frac{1}{L}\int v \; dt$$

Like this,

$$Is = \frac{1}{L}\int \frac{dP}{dt} \; dt$$

Which simplifies to demonstrate that the short-circuit current in the circuit (***Is***) is a direct measure of position of the magnet relative to the coil.

$$Is = \frac{P}{L}$$

2. Returning to Faraday's law, if the change of flux is created by a sinusoidal groove modulation of amplitude (***A***), then the output voltage of pickup is given by,

$$E = \frac{d(A \sin \omega)}{dt} \cdot k$$

$$= k.\omega \,.\, A \cos \omega t$$

in which, the independent term ***ω*** indicates that the signal amplitude increases with frequency; just as we expect from a velocity-sensitive transducer.

The short-circuit current in any electrodynamic generator obeys Ohm's law such that the current is determined by the induced voltage divided by the impedance of the generator.

Thus, it is determined by dividing the above by the impedance of the generator which, to start with, we will consider to be entirely the reactance (***X***) of the inductance (***L***). This is determined by the well-known equation, $X = \omega \,.\, L$

Thus, the short-circuit current, (***Is***) will be,

$$Is = \frac{k.\omega \,.\, A \cos \omega t}{\omega L}$$

It's clear that in this equation, the ***ω*** terms cancel-out and the transfer-function of the pickup is rendered *independent of frequency*.

But the equation for ***Is*** is incomplete because the short-circuit current is determined by both the real and the imaginary parts of the pickup impedance. The equation below incorporates the resistive part of this impedance (***r***).

$$|Is| = \frac{k.\omega \,.\, A \cos \omega t}{\sqrt{((\omega L)^2 + r^2)}}$$

At the frequency that the reactance of the inductive coil (**L**) falls to that of the resistance of the coil (***r***), the pickup returns to velocity operation with the magnitude of the response falling away to zero at DC as required. Provided the cartridge coils are wound with ratio of resistance (***r***) to inductance (***L***) such that

$$L / r = 3180 \times 10^{-6}$$

this will compensate for the recording characteristic. (3180µS is the expression of 50Hz as a time-constant).

3) The power delivered into a phono cartridge from the record modulations is of the order of a milliwatt, whereas the power dissipated in the impedance of the **DisC** cartridge is designed to be of the order of a microwatt. The conversion efficiency is therefore a fraction of a percent and too small for there to be any significant reflection of the electrical load back to the stylus. Direct measurements of the **DisC** phono cartridge confirm that there is insignificant effect upon the tracking-ability when operated into a short-circuit load. •