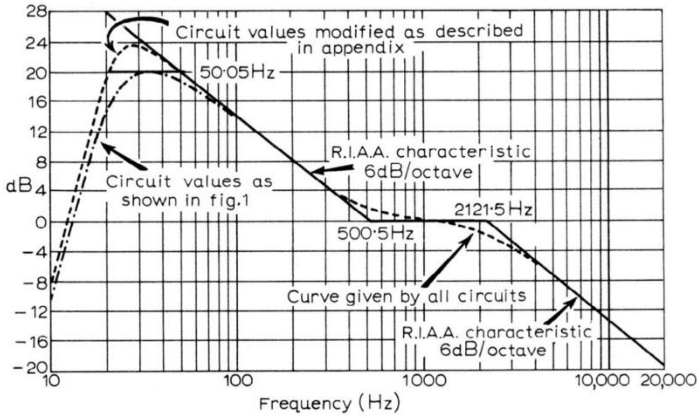
Afterword 20
Revised RIAA equalisation

Linsley Hood's RIAA

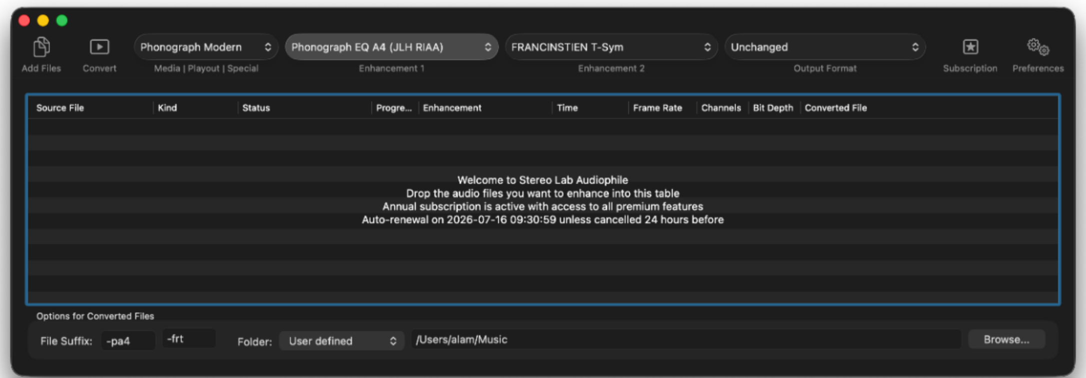
Version 4.3.0 of the **Stereo Lab** app' is now available with an important new RIAA equalisation option. This version of RIAA is based on original work by John Linsley Hood, hence the label JLH-RIAA.[1] To quote Linsley-Hood,

> *Although the RIAA replay characteristic suggests an approximately flat velocity response from 20Hz-50Hz, ... the author suspects that this is not done, a constant modulation characteristic being used instead. The author has therefore, for his own use, modified the values of the feedback elements [to accomplish this].*

Linsley Hood's revised frequency response is compared with standard RIAA in the following graph from his article.



This new option is implemented in software and is labelled EQ-A4.



[1] Modular Pre-amplifier Design. J. L. Linsley Hood. Wireless World, July 1969.

Justification

Linsley Hood designed other RIAA preamplifiers after his first attempt in 1969. His later, modular design, which was intended to replace his design of 1969, did not incorporate this non-standard option.[2] He is not explicit about this change of heart, so we don't know if he repudiated this opinion later on. Whatever his own journey, from our point of view, we think he was onto something in the earlier design. But it has taken a long time for us to realise this, which is why this EQ is a late addition to **Stereo Lab**'s range of equalisation options.

The LP record was introduced in June 1948 at press conference in the Waldorf Astoria, New York. The first stereo LP records appeared ten years after that. But stereo wasn't widely adopted as a commercial medium until the end of the 1960s. The widespread adoption of stereo forced the implementation of correctly engineered RIAA equalisation via a commercial mechanism. To quote from an earlier chapter of the **Needle-drop Handbook**,

> *Equalisation crystallised with the introduction of stereo records because the change from mono spelt the death knell of many of the smaller lathe manufacturers and the retirement of older, mono lathes with miscellaneous equalisation circuits.*

In the twenty years during which the LP record was – effectively – a mono only format, many mastering houses modified their 78 RPM lathes and cutting heads so that they could cut the new $33^1/_3$ RPM format. A record lathe and its associated cutter head were very expensive pieces of equipment and there was an enormous commercial incentive so to do. We know lathe manufacturers produced conversion kits to modify the lathe turntable to run at the lower speed, with finer pitch lead screws,[3] and we have documented evidence of the development of commercial, external equalisers intended to modify 78 RPM cutter-heads, fitted with microgroove cutting styli, to the new LP recording characteristics.[4]

In our own archiving work, we have noticed that many early, mono LPs do seem bass light. And we suspect that Linsley Hood may have been right that a constant modulation characteristic was used all the way to the lowest frequencies. This suspicion is supported by the fact that, all but a very few, 78 RPM records were equalised as constant amplitude below the *turnover* frequency; see chapter ten. One can imagine that mastering studios, faced with the introduction of the LP record, modified their lathe electronics to shift the breakpoint of constant-amplitude groove to the 500Hz RIAA standard (from the older 300Hz turnover) and to add high frequency preëmphasis.

---

[2] Modular Preamplifier. J.L Linsley Hood. Wireless World, October 1982 – February 1983. Instead of arguing for a modified LF characteristic, Linsley Hood chose to argue for a shunt-feedback RIAA equaliser which was a quixotic (and forlorn) personal crusade.

[3] After the invention of the LP record, Scully 501's (first introduced in 1938) has leadscrew options for 78 RPM and $33^1/_3$ RPM records.

[4] Crossover Filter for Disc Recording Heads. Roys, H.E. Audio Engineering June 1949. This equaliser was intended to convert the RCA MI-11850-C moving-iron cutter to cut the NAB characteristic.

Built-in turnover

Many of these older lathes and cutter-heads did not implement turnover equalisation electrically, as did the flat velocity-response negative feedback-controlled cutter-heads used later.[5] In these older systems, equalisation was mechanical. This was true from the very earliest electrical cutter as described in the paper that introduced electrical recording.[6]

Cutter operation

Let's consider the physical operation of an electromagnetic cutter.[7] The driving Lorentz force (→ voltage drive) in Newtons acting on the coil in the gap in the magnet is given by this expression, **F** = **B L i**, where **B** is the magnetic flux density (in teslas), acting perpendicularly to the wire, where **L** is the length of wire (in metres) contained within the magnetic field and **i** is the current in the wire (in amps).

Below the resonance of the mechanical cutter system (which was inevitably set in the midrange, see chapter six), frequency response was dominated by the effective mass of the moving system and the centring means. It was thus *compliance controlled*: applied force resulted in directly proportional armature deflection. The cutter stylus acted according to Hooke's law, and lower frequencies were recorded with equal amplitude.

Above resonance, the cutter mechanical system was *damping controlled*, whereby a constant applied force resulted in decrease in amplitude of deflection inversely proportional to frequency. The motion thereby became approximately *constant in velocity*. The description of the range of constant velocity operation was explained at the time as being *mass controlled*.[8] This is incomplete. If the drive force were truly constant and the response of the cutting stylus was mass controlled, the frequency response would be *constant acceleration above resonance* (think of **F** = **m**.**a**). We saw exactly this effect with a moving-coil loudspeaker in afterword ten. The various cutting laws are defined formally in appendix one, and the physical system of the cutter head is analysed in appendix two.

---

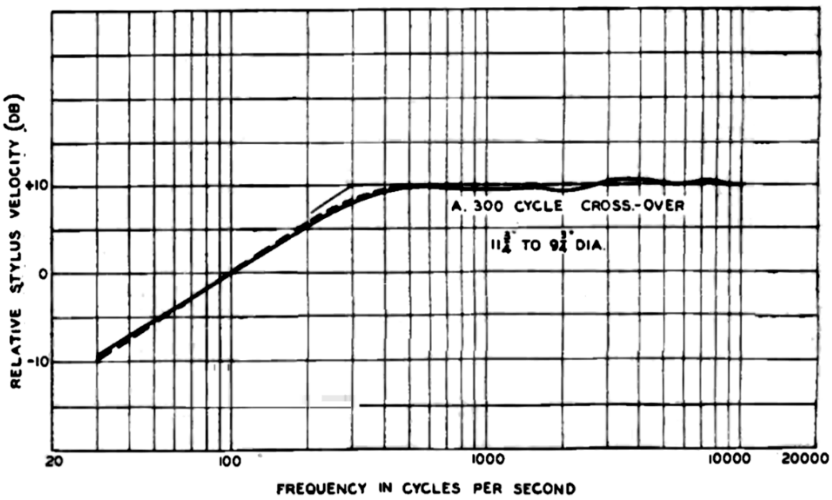
[5] The Development of Disc Cutting Heads. Davies, S.W. Audio Engineering Society Convention Paper 5751. Presented at the 114th Convention 2003 March 22–25 Amsterdam, The Netherlands.

[6] High Quality Recording and Reproducing of Music and Speech. J. P. Maxfield and H. C. Harrison. Bell Telephone Laboratories Report 1926. The cutter-head armature system was terminated by a long rubber line, made of concentric tubes of rubber. See appendix two.

[7] We have chosen to describe the action of a moving-coil cutter here whereas, in the period we are considering, many of the cutters would have been moving iron rather than moving coil. The reason is to simplify the mathematical model. A moving iron device relies on the tendency of the iron armature to move towards a region of higher magnetic flux. The force is related to magnetic energy/reluctance rather than directly to the Lorentz force on the conductor in a moving coil type. From a physical perspective, apart from the non-linear terms in the moving-iron cutter in which the pole pieces create a square-law negative compliance (due to magnetic attraction), the two cutter types are comparable.

[8] Crossover Filter for Disc Recording Heads by Roys (op. cit.).

Mechanical damping in a variety of forms and designs was used to control the height of the resonance peak between these two regimes, to obtain a smooth characteristic between the low-frequency, constant-amplitude and high-frequency, quasi constant-velocity portions. The velocity response vs. frequency of a commercial cutter is illustrated.[9]

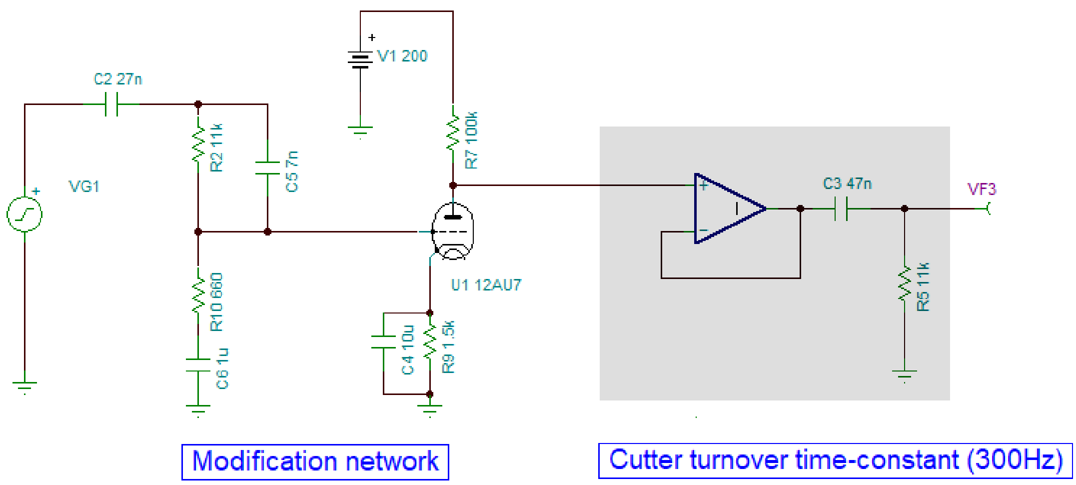


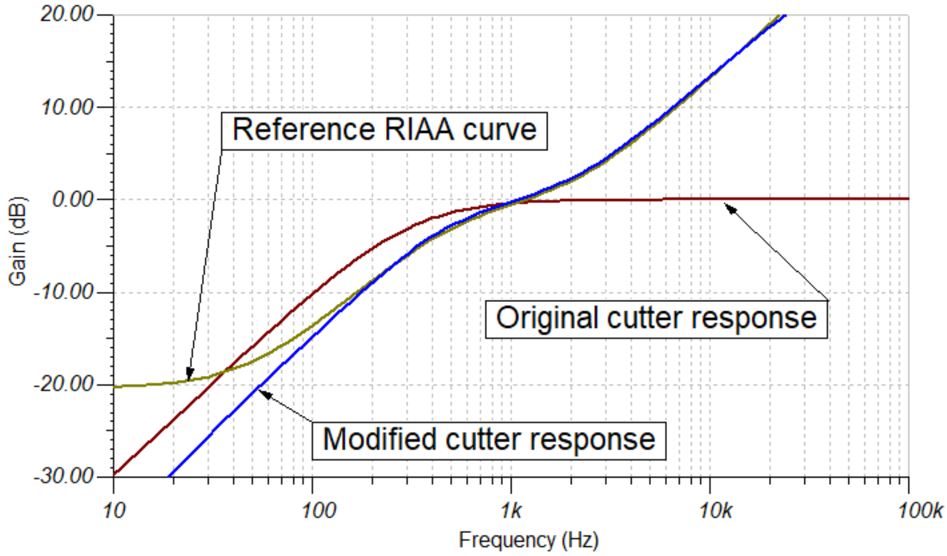
Modifying such a cutter system to cope with the requirements for the new plastic records wasn't a simple matter. It would have taken a brave engineer indeed to attempt to modify the mechanical system. Instead, an extra equaliser and amplifier stage were necessary – the (valve) amplifier to provide the extra make-up gain for the lossy HF preëmphasis network, and a further LF breakpoint added to approximate raising the old turnover frequency of 300Hz to 500Hz for the new medium.

At the remove of eighty 80 years, of course, it isn't possible to know how the various mastering houses tackled this. But we have attempted to design such an equalisation stage. We have assumed the old *300Hz turnover is not modifiable directly*. Whether or not this was electrical or mechanical in nature, we have taken the attitude that we must absorb that part of the original transfer function in developing the overall RIAA response (it is illustrated electrically in the grey box in the schematic below).

The circuitry for an equaliser design and the modified response is compared with the original cutter response and a reference RIAA record equalisation curve below.

[9] Crossover Filter for Disc Recording Heads. Roys, H.E. Op. cit. See appendix one for a mathematical treatment of the various cutting laws.





The modified response matches the required RIAA curve well over the 100Hz to 10kHz range. But it does diverge below 100Hz where a constant amplitude characteristic is implemented.

The extra low frequency pole-zero formed by C2 with R2 + R10 implements the turnover frequency to 500Hz. At first, we wondered if we might cascade an extra high-pass stage to modify the original transfer function of the form,

$$H(j\omega) = \frac{j\omega\tau}{1 + j\omega\tau}$$

to produce this overall transfer function,

$$H(j\omega) = \frac{(j\omega)^2\tau_1\tau_2}{(1 + j\omega\tau_1)(1 + j\omega\tau_2)}$$

Where τ_1 represents the time constant relating to the 300Hz turnover (530µs), and τ_2 represents the necessary added external time constant. If we work through the maths, the ideal (rational) frequency for this second pole is 343Hz. But this results in a 12dB/octave filter which isn't what we require here. In fact, there is no analytical solution of the cascaded transfer function equation which will give exactly the single-pole 500Hz turnover response.[10] So instead, we added component C6, which implements a complementary pole-zero pair which cancel the original 300Hz physical turnover (see afterword six).

It is not possible to implement the flat-velocity response from 20Hz-50Hz in the RIAA characteristic in this type of circuit – because the 300Hz turnover is "baked in" and the response falls away to DC with unforgiving inevitability. This is presumably what Linsley Hood meant when he wrote,

> *Although the R.I.A.A. replay characteristic suggests an approximately flat velocity response from 20Hz-50Hz, this would effectively imply recording bass lift in this region, and the author suspects that this is not done.*[11]

This comment seemed confusing to us for many years, and accounts for our late conversion to this point of view. A constant velocity recording below 50Hz *does not automatically imply bass-boost*. Only if it is seen in the context that we have given here – that the groove cut was inherently constant amplitude below the turnover frequency – does this comment make sense. In this scenario, Linsley Hood is right: the only way to have implemented the bass shelf in a modified cutter head would have been to add a further bass boost circuit – a strategy that would have predictably introduced hum, distortion, and low frequency stability problems, and is unlikely to have been popular.[12]

It therefore does seem probable (perhaps almost inevitable) that older cutter-heads modified for the 1948 LP medium would not have implemented the RIAA bass shelf, and this situation would have lasted the best part of twenty years.

AES curve

Further evidence for this argument exists in the AES playback characteristic (see p. 397 of the **Needle-drop Handbook**.) The AES characteristic (400-12) was not a recording characteristic: it was replay-only standard. The American Audio Society's laudable idea was to try to get playback equipment manufacturers to standardise on a playback characteristic, thereby forcing the record manufacturers to normalise their

---

[10] There exists an approximate solution using an added low-frequency pole at ≈130Hz. This approximates the correct response between 500Hz and 100Hz, by implementing a heavily damped 12dB/octave filter with a turnover at 500Hz. But the ultimate rate of attenuation is 12dB/octave which creates a *constant absement cut* below 100Hz. (See appendix one for a definition of absement).

[11] Modular Pre-amplifier Design. J. L. Linsley Hood. Wireless World, July 1969.

[12] Low frequency instability problems derive from very large stylus modulations at low frequencies in the constant velocity range. The risk of the moving iron cutter armature approaching the magnet assembly to the point where the armature snaps to one or other of the pole pieces is a real danger. Before this disaster, clearly THD rises dramatically as is the non-linear (square-law) force attracts the armature to the pole pieces.

equipment on the recording side. Their plan worked well, at least in the USA, where American manufacturers embraced this idea with vigour.

But note: the AES replay standard *does not include a bass-shelf*. Instead, the low frequency boost on the replay side continues at 6dB per octave. To quote the AES notice in Audio Engineering magazine,[13]

> *It is expected that the characteristic at the low-frequency end will stop rising at the 6db/octave rate at some frequency determined by the range of the reproducing equipment. It is felt that first-class wide-range equipment will continue to 30 cps within the specified tolerance and then flatten off as rapidly as possible*

In **Stereo Lab**, the JLH-RIAA equalisation, follows the AES committee's advice and continues at 6dB/octave to a lower limit of 25Hz.

Conclusion

Certainly, many mono LPs do sound better balanced using this equalisation – an opinion that John Linsley Hood clearly held in 1969 when a substantial proportion of his record collection must have included older, mono records. At any rate, it is clear that JLH-RIAA is a useful addition to comprehensive equalisation options available in **Stereo Lab**.

Appendix 1 – Groove cut laws

Let the groove displacement be $x(t)$, and let the cutter drive signal be a sinusoid at angular frequency ω:

$$s(t) = \sin(\omega t)$$

The different "constant-·" cutting laws are defined by which physical quantity has frequency-independent amplitude.

Constant amplitude cut

The groove displacement itself has constant amplitude. So,

$$x(t) = A\sin(\omega t)$$

where A is independent of frequency. This means velocity amplitude $= A\omega$, so higher frequencies produce larger velocity and a larger electrical output from a velocity-sensitive transducer (like an electrodynamic pickup).

Constant velocity cut

The groove velocity has constant amplitude. This requires,

[13] AES Standard Playback Curve. Audio Engineering. January 1951.

$$\dot{x}(t) = V \cos(\omega t)$$

Integrating,

$$x(t) = \frac{V}{\omega} \sin(\omega t)$$

So, groove displacement falls as $1/\omega$, and displacement amplitude $= V/\omega$

This is the classic acoustic phonograph-recording law over most of the audio band. Remember that a constant sound pressure level from an acoustic reproducer (which was still the most common type at the time of the introduction of the LP – at least in European countries and their empires) requires a record cut to *constant velocity*. Frequencies cut below the traditional turnover transition (at 300Hz) to constant-amplitude were gradually attenuated when reproduced acoustically.

Constant acceleration cut

The groove acceleration has constant amplitude. This requires,

$$\ddot{x}(t) = -G \sin(\omega t)$$

Integrating twice,

$$x(t) = \frac{G}{\omega^2} \sin(\omega t)$$

So, displacement decreases as $1/\omega^2$. Velocity amplitude $= G/\omega$, and displacement amplitude $= G/\omega^2$

General law

In general, if the n-th derivative of groove displacement is held constant in amplitude, then:

$$x(t) \propto \omega^{-n} \sin(\omega t)$$

with:

- $n = 0$: constant amplitude/displacement
- $n = 1$: constant velocity
- $n = 2$: constant acceleration
- $n = -1$: constant absement/integral of displacement.

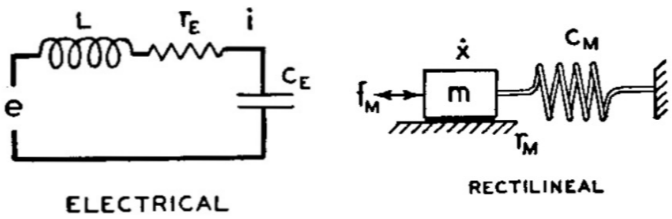
So, the four cutting laws are:

Cutting law	**Groove displacement $x(t)$**
Constant amplitude	$A \sin(\omega t)$
Constant velocity	$\frac{V}{\omega} \sin(\omega t)$
Constant acceleration	$\frac{G}{\omega^2} \sin(\omega t)$
Constant absement	$B\, \omega \sin(\omega t)$

The time integral of distance (more precisely, position) does not have a universally standard everyday name like velocity or acceleration. Physicists call his quantity the *absement* (“absence” + “displacement”). It measures how far something is away from a reference point for how long. Its units are distance × time, such as metre-seconds. We think of a *constant absement* cut as a *constant area* cut.

Appendix 2 – Mechanical system

The simplified mechanical system of the cutter and its electrical circuit analogy are illustrated.[14]



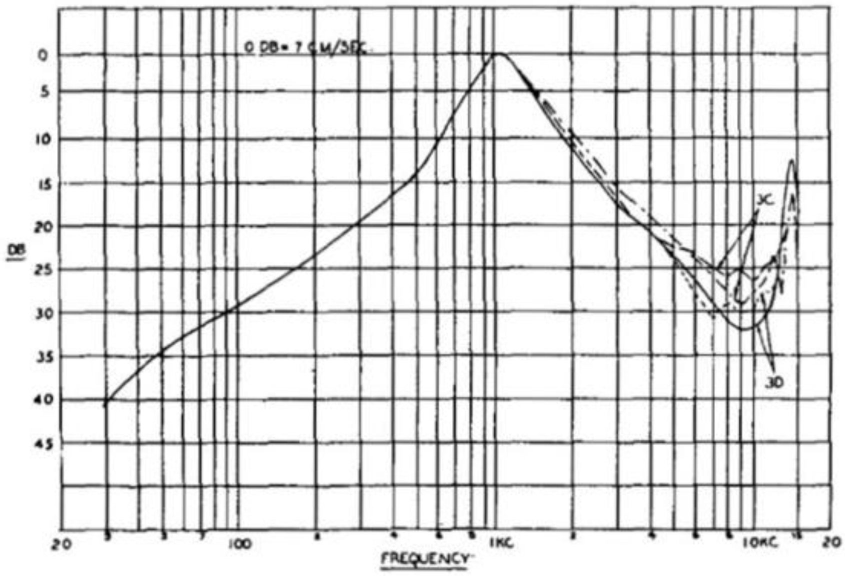
As noted in the main text, if the drive force were truly constant, the response of the circuit was compliance controlled below resonance and mass controlled above, the frequency response of this circuit would be: *constant displacement* below resonance, and *constant acceleration above resonance*.

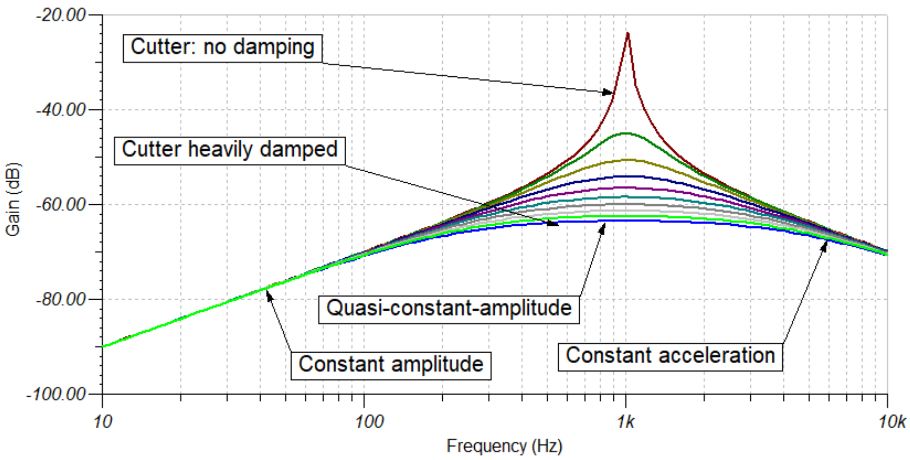
This is illustrated by the measured response of an undamped Westrex 3C/3D cutter and the upper curve in the simulation graph below.[15] Both these graphs illustrate the velocity (circuit analogy of current) of the cutter to force (circuit analogy of voltage) excitation across the frequency spectrum.[16]

[14] See: The Development of Disc Cutting Heads. Davies, S.W. Audio Engineering Society Convention Paper 5751. Presented at the 114th Convention 2003 March 22–25 Amsterdam, The Netherlands, for more comprehensive electrical analogies.

[15] The Westrex cutter is undamped because it is here measured without its feedback control mechanism.

[16] We used the following mechanical parameters (and their electrical analogues) as follows: moving mass 5g (5mH); compliance 5μm/N (5μF). The scale of the graph is not calibrated: it represents the voltage across a very low value resistor in series with the other components – so as to measure current (representing velocity). We discovered that a damping resistance of ≈ 100N/m/s ($100\Omega_{mech}$) is necessary to obtain something approaching a constant velocity response in the midrange. However,





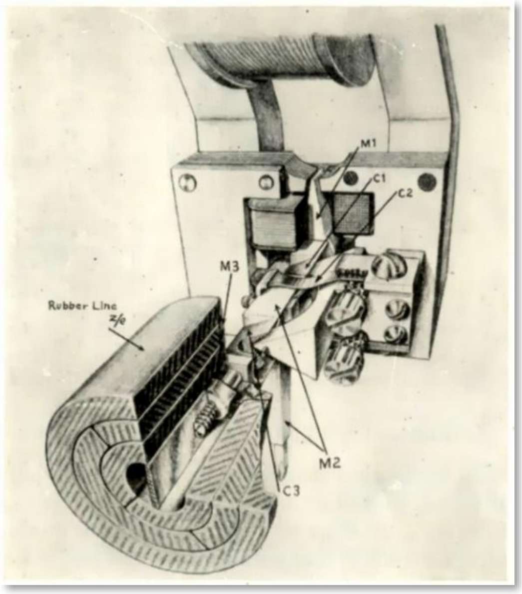
Clearly a cutter-head with this undamped frequency response would be useless as a practical recorder. In the case of the later Westrex 3C/3D heads, damping was achieved using an electromechanical servo (feedback) system.

Before feedback-controlled heads, a practical instrument was obtained by very significant physical damping of the moving parts with elastomers, oil, oil-soaked paper, and grease in the magnetic gap – illustrated by the family of curves in the simulation response. This damping depressed the resonance to a degree that a flat (quasi constant velocity) response was obtained over the majority of the passband with a compliance controlled, constant amplitude “skirt” at lower frequencies and a tolerated “droop” at high frequency as the response reverted to constant acceleration.

---

in practical cutters, the damping wasn’t simply resistive, it often incorporated reactive impedance (compliance) in the form of elastomeric components.

The engineering effort expended on suitable damping was considered the true "art" of cutter-head design. In Maxfield and Harrison's description of the Westrex system cutter, the authors are clear that they consider the damping of the electromechanical cutter (in which the cutter-head armature system was terminated by a long rubber line, made of concentric tubes of rubber) as the principal innovation in their design.[17] The cutter and a cross-section of the rubber transmission line damper are illustrated left.[18]



Larry Scully recalled that the Westrex head was, "*a closely guarded top-secret, which no outsider could ever set eyes upon, all recording companies at that time, locked their cutting heads away overnight in the safe, together with the cash and the trade acceptances.*"[19]

Parting thought

Significant power issues arise from the enormous levels of preëmphasis that the RIAA equalisation demands. Any cutter-head modified in the way we have described above must have required very careful handling by the mastering engineer to avoid overloading the cutting amplifier and cutter head. This, no doubt, accounts for the relatively low recorded levels of this era of LP records. We further suspect that only part of the RIAA treble-boost was implemented in the interests of practical cuts. There is quite likely a corresponding story to be told at the top end of the cutter response.

[17] High Quality Recording and Reproducing of Music and Speech. J. P. Maxfield and H. C. Harrison. Bell Telephone Laboratories Report 1926.

[18] It is also noteworthy – given his genius for circuit design – that when Alan Blumlein was employed by Columbia in 1929, principally to design a recording system which did not infringe the Bell Telephone/Western Electric patents, he chose an electrical solution – rather than rely on mechanical damping. (British Patent No. 350,998.) The Blumlein head together with its associated microphone and amplifiers became the standard recording system for the newly formed EMI Company from 1932 onwards.

[19] He Who Lathes Best. High Fidelity Magazine December 1956.