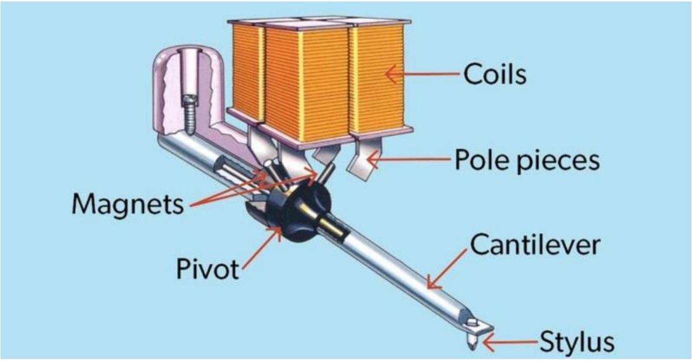
Dividing MM Carts into electrical parts with individual Transfer Functions



Bill Shurvinton,
Dagfinn Rasmussen,
Hans Polak

04/04/2023

Introduction:

A moving magnet (MM) phono Cartridge can be seen as composed of two important parts, a stylus/cantilever assembly and the electrical part receiving the cantilevers signal, the latter hereafter indicated as Generator.
The goal of this paper was to find out whether those two parts influence each other or can be viewed as independent.

Conclusions:

1) The underlying paper has shown that the coupling between Cantilever and Generator is so weak, that the interaction from one to the other or mutual feedback can be regarded as negligible .

2) An often referenced model of a resonating needle/cantilever, electrically corrected by a Generator with a much narrower FR, has been shown to be wrong.

3) The Cantilever assembly's model that came out of the investigation also gave new insights for a plausible explanation why Carts sag in their FR around 5Khz.

4) The beauty of having an accurate replacement diagram for the Cantilever plus Generator is that all kind of loads can be simulated and optimized for the best possible response.

Content

1)	**Replacement diagrams for the MM Cartridge Generator.**	**3**
2)	**Measuring the Frequency Response of the complete Carts**	**4**
3)	**Determining the Transfer function for the Cantilever assembly**	**6**
4)	**Constructing the replacement diagram for the Cantilever Assembly**	**6**
5)	**Terminating the Cart with a load much smaller as 47K (Damped Loading)**	**11**
6)	**Comparing the model in this paper to another model.**	**14**
7)	**Further areas for research**	**15**
8)	**Consulted literature**	**15**

1) Replacement diagrams for the MM Cartridge Generator.

Some simple measurements have shown that the factory specifications for cartridge generator parameters, particularly inductance and resistance are generally inaccurate. Therefore the first step was in making replacement diagrams for Generators using a Vector Network Analyzer. This is where the whole exercise started.

Bill, having a large collection of all sorts of Carts, made available eight totally different carts for measuring, see link below:

[https://www.diyaudio.com/community/threads/cartridge-dynamic-behaviour.320026/page- 72#post-5792099](https://www.diyaudio.com/community/threads/cartridge-dynamic-behaviour.320026/page-72#post-5792099)

As a result of one of the first tests done it was seen that it made no difference at all whether the cantilever assembly was attached or not, not even in the tiniest details, although the used VNA measured up to 10MHz with high accuracy.
One can also put a signal on a generator, but that will never lead to a moving needle.
So the Generator "doesn't see" the Cantilever assembly.
The question to be answered was whether the opposite is also true, i.e. does the Cantilever assembly see the Generator in such a way that its behavior depends on the Generator's load ?
Tests done with one channel shorted, indicated that the 'electrical damping' sometimes discussed does not appear to exist, but further testing was required.

A circuit diagram emerged whose topology could be used to represent all Cart Generators.
One example is shown below, representing the replacement diagram of the Audio Technica AT150.
At the upper left with VNA´s measurement results, ultimately leading to the replacement diagram in LTSpice, which accurately replicates the VNA results and give a far more accurate generator electrical model than previously available

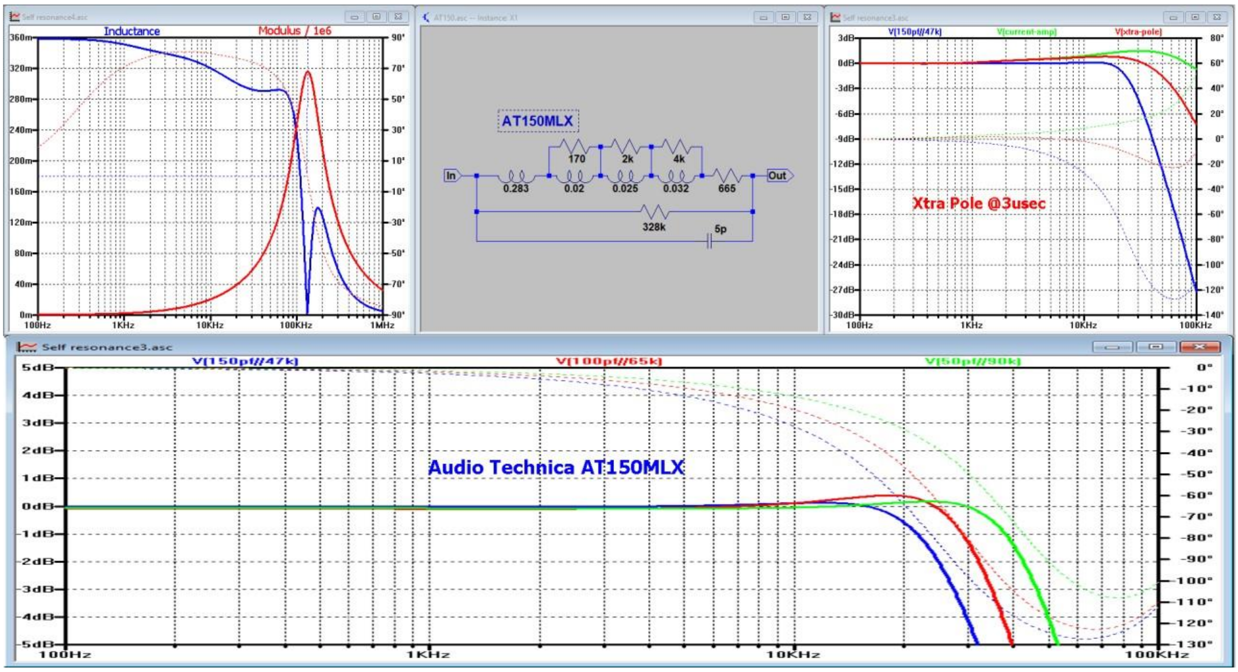


Figure 1 Exploring the AT150´s generator

Injecting these simulated generators with a signal, results in a FR depending on their load, said load being the total interconnect capacity plus the preamps input capacity plus input resistance. A 47K resistance is mostly used as load resistance. However, the resulting FR depends strongly on this load as can be seen in the lower part of the image.
When measuring the FR of a complete Cart, it is therefore important to exactly know the loading termination.

Alternative termination configurations are also possible, such as using a much lower load resistance thereby almost eliminating the effect of the total load capacity, a damped load as it´s sometimes called. [6]
When using a resistance where Rload and Lcart form a 75µsec pole, ca. 4K in case of the AT150, the 75µsec pole in the preamps Riaa network can be discarded, but other pole frequencies can also be used, but then they will need added and a more complex compensation in the preamp.

The upper right corner of Fig1 shows both options using the full Riaa compensation terminated with 47K//150pF in blue and a version terminated with ca. 4K without the 75µsec pole in the Riaa network, almost insensitive to the capacitive generator termination in green.
To "tame" the extended FR somewhat, the effect of an extra 3µsec pole is also shown in red.
Although these FR images are still without cantilever, looking at all the images in the above given DiyAudio link may indicate that not every cart may be happy with the 75µsec loading. This will largely depend on the properties of the used cantilever/generator combo and explains why this loading scheme has been proposed several times but never really taken off. Currently the authors are only aware of one non-DIY phono stage using this loading scheme, made my Phaedrus audio and only usable on one model of AT cartridge.

Dagfinn, doing all the cartridge's FR recordings , started with a Luxman, but since we needed a very accurate termination, a Moon 110LP v2 preamp was modified, settable resp. to 50pF, 150pF, 270pF and 370pF parallel to 35K, 47K, 58K, 67K, 81k and 100K.
FR was made to be within 0.1dB accurate up to 100kHz.

2) Measuring the Frequency Response of the complete Carts

One of the biggest problems found in measuring cartridge frequency response is a suitable test record. Many of those from the 'golden era' of vinyl have potential anomalies that skew results. For this testing we used an Riaa corrected pink noise recording from 500Hz to 30kHz on a 45rpm disk from CH Precision. This was computer generated in order to provide accuracy that is rare to find in a test record.
Pink noise has equal energy per octave, and when displaying the FR with a FFT having fixed frequency bin widths, it will show as a negative slope of 10dB/decade.

To verify the correctness of the recorded signal on this disk, record was played back with a Benz LP MC cartridge, whose FR is specified from 10Hz-50Khz within 1dB.
Figure 2 seems to fully confirm that the Disk can be used for our purpose as a reference.
Up to 28.5Khz the response is within +/- 0.5dB and from there -1.5dB@30Khz.

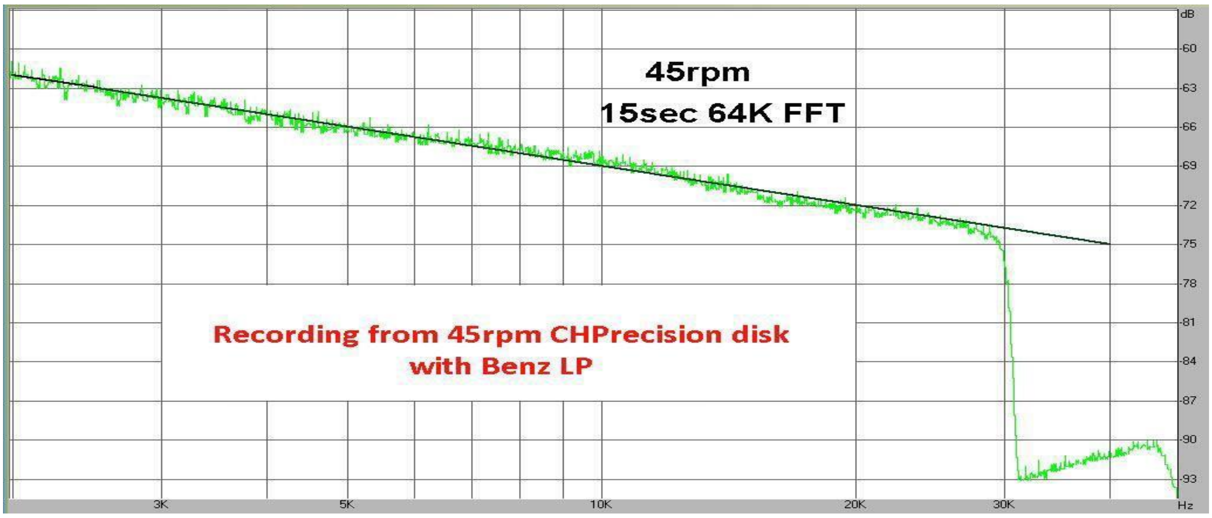


Figure 2, checking the Test signal on the CHPrecision test disk.

To get a better view on the spectrum, the recorded FR was rotated within Audacity by multiplying it with an upgoing 10dB/dec slope to facilitate comparing it to the FR generated by the simulated Generator model.

The first Cart measured was an AT24 with a custom made sapphire cantilever assembly.
This one with a higher moving mass than the factory cartridge was chosen to try and amplify any mechanical anomalies.
Figure 3, the FR of the recording in purple and the FR simulated for the Generator, both on exactly the same scale.

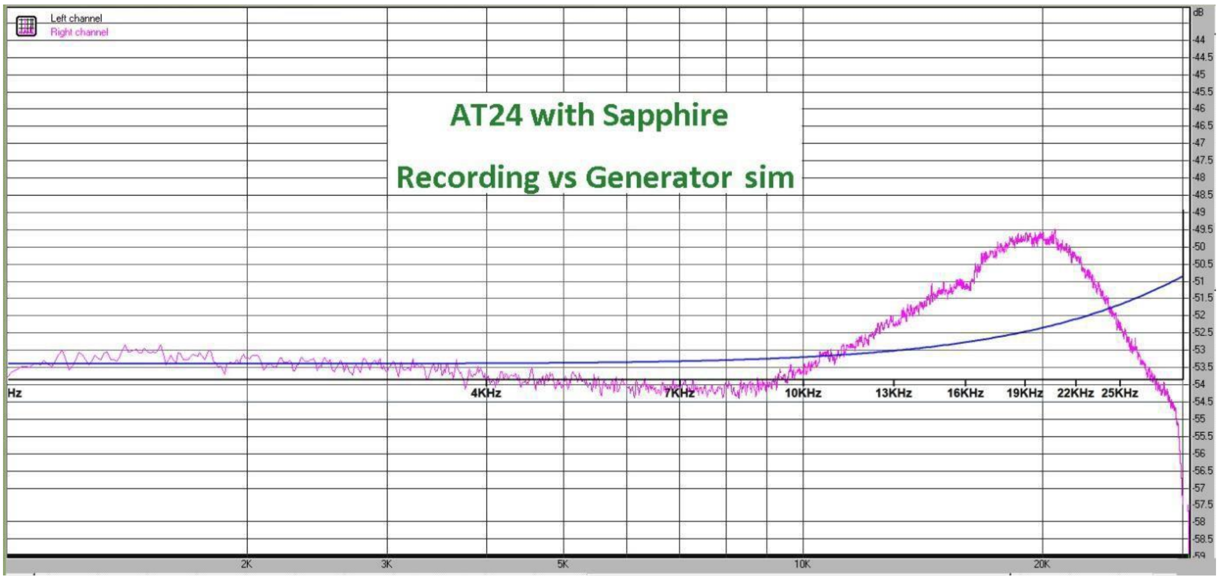


Figure 3, recorded FR with AT24 and simulated FR for its
Generator, both for 48K5//192pF.

So because of the Cantilever assembly adding its transfer function*, the difference between the two has to be caused by this Cantilever assembly's TF.*

3) Determining the Transfer function for the Cantilever assembly

So, to get the assembly's transfer function, the next step had to be in subtracting both curves, the Generator's FR from the Recorded FR. Neglecting the small dip at around 16kHz in figure 2 and figure 3 that turned out to be disk related, the TF for the Cantilever could now be determined up to 30kHz.

Now doing the same exercise for a AT22 with the OEM Beryllium cantilever and and also for a Denon DL-107 and a Denon DL-109 resulted in the FR's for four Cantilever assemblies.

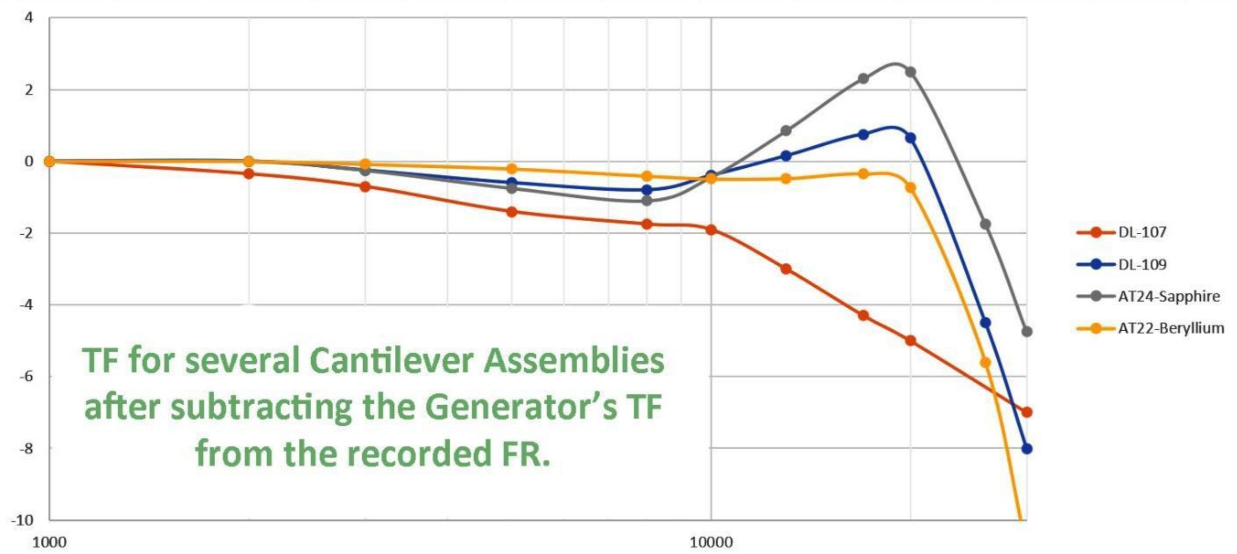


Figure 4, Frequency response for four Cantilever assemblies.

Note that the AT-22 was a high end MM from the late 70s designed for light tonearms and the DL-107 was a radio DJ cartridge of the same vintage as the DL-103 MC and designed for heavy tonearms and limited frequency response. This gave a good spread of available designs with only a few tests

4) Constructing the replacement diagram for the Cantilever Assembly

With the above gathered data, an electrical analogy can be constructed describing all four models with one and the same topology by just changing component values.
In order for this to be accurate a few factors need to be taken into account.

a) When frequency goes up on a RIAA recorded LP, velocity and acceleration are increasing for a given input level. This causes the indentation of the vinyl to becoming deeper from acceleration forces in the concave or the tip's pushing part as opposed to the force and indentation of the sine wave's convex part.
As a consequence the tip does not follow exactly the center of the track but deviates depending on the frequency and tip mass, *which manifest itself as a lower amplitude*.
This seems to be the reason for the dip that many Carts are showing in their TF somewhere

between 5Khz and 10Khz.

In picture 5 below, a round stylus tip is shown sitting in a groove, where in Red the contact areas are visible from above between tip and groove wall.
The black line under the tip is the route that the tip should follow, but because of indentation of the elastic convex wall being exposed to high acceleration forces on a very small contact surface, the stylus in fact follows the red dotted line.
By making this short cut, the Cart will produce a smaller signal as was envisaged.
With increasing frequencies, the contact area because of indentation will increase rapidly, diminishing the force per square surface unit, causing that indentation will come to a halt as from a certain frequency.

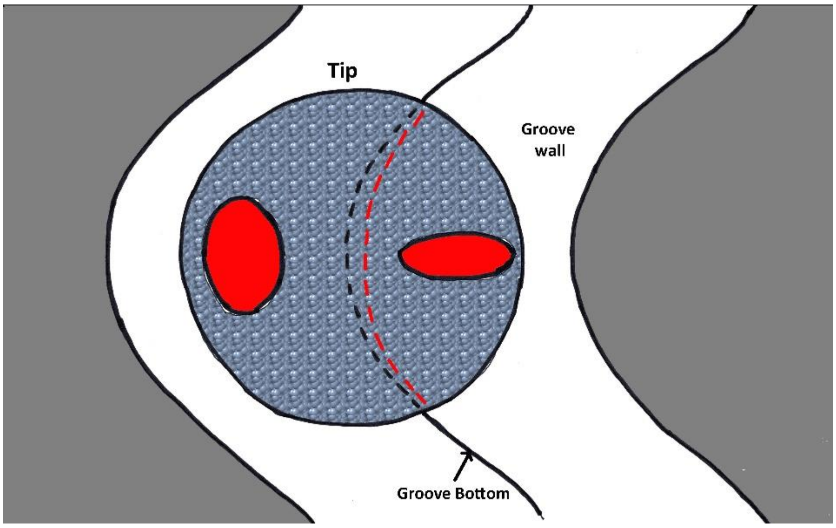


Figure 5, The shortcut the tip takes because of indentation

b) Further increasing frequency, a Stylus/groove resonance fr causes the Cart's output to increase again.

$fr = (0.632/\pi Sqrt(m) * (E_0^2 F_v R)^{1/6}$ **[4]**

With m the equivalent tip mass.
Eo the Young modulus, 3.76e9 N/m² for vinyl
Fv the the stylus force, usually 2 gram
R is the tip radius touching the track wall.

fr is thus proportional to $Fv^{1/6}$, the higher the stylus force, the higher fr, independent of track speed.

c) Then there is a third mechanism called fc, the cutoff frequency where the cart produced no output.
Think of a free mass attached to a spring. When increasing the excitation frequency, the mass has the same direction of movement while the phase shift gets larger and larger, up to the point where the mass stops moving. Further increasing the frequency causes the mass to move in opposite direction.
This is what happens between the vinyl “spring” and the tip mass.

$fc = 1.51(V/\pi)*(E_0/F_vR)^{1/3}$ **[4]**
V is the track speed.
fc is inversely proportional to $Fv^{-1/3}$, the higher the stylus force, the lower fc
Q of fc is set at 0.88

Because of V, fc is a dynamic parameter depending on rpm and position on the Vinyl record.
In our test we are using a 45rpm disc at 16,5 cm diameter, causing Fc to be 46 Khz for a 0.65 mil round tip.
To show the huge dependency on rpm and position on the record for this 0.65mil tip, going from 60Khz to almost 20Khz, see below figure 5.
In comparison, for a 5um Shibata tip you can multiply all fc values by 1.5.

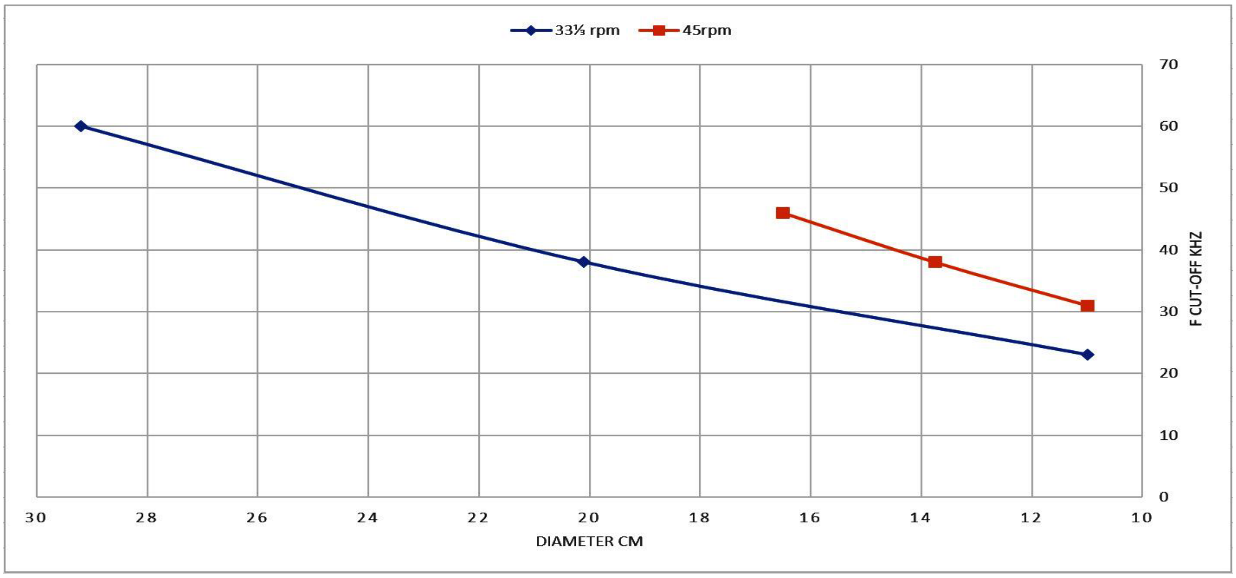


Figure 6, Cut-off frequency dependency on rpm and position for a 0.65 mil round tip.

Adding all the above together, leads to a generic replacement model for Cantilever, Generator and Termination as shown in fig 7.

There are other models found in papers [1], but none of them were able to fully match the tested Carts from figure 3.

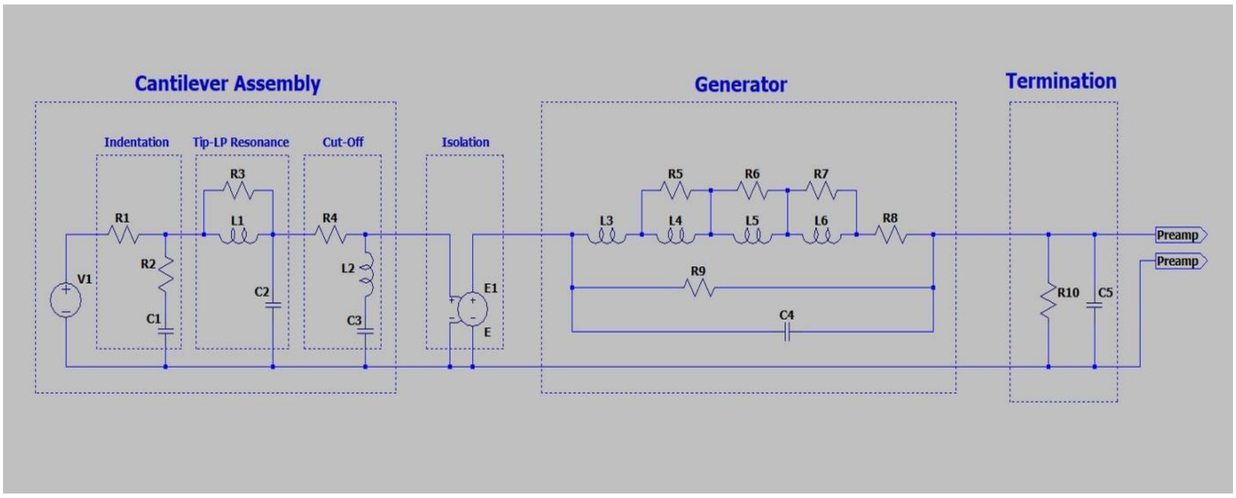


Figure 7, Generic model for Cart plus termination

Now entering the right component values into this generic replacement diagram for the AT24 with sapphire cantilever, gives exactly the same overall FR as the recorded one, just because it was constructed that way by subtracting the Generator's FR from the recorded FR. With a 0.24mil elliptical mil tip, fc was 64Khz at the used position on the 45rpm record.

This results in the circuit diagram below.

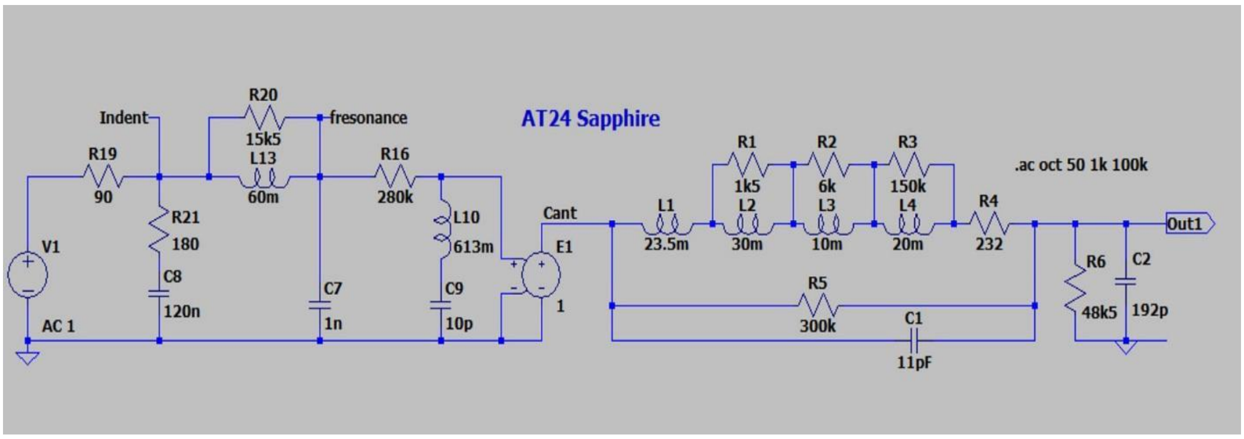


Figure 8, Circuit diagram for a AT24 with Sapphire cantilever and 0.24 mil elliptical tip

Frequency responses are shown below in figure 9 for resp. record Indentation in Red, Tip-LP Resonance in Blue, Cutoff in Green and the resulting overall response in Teal.

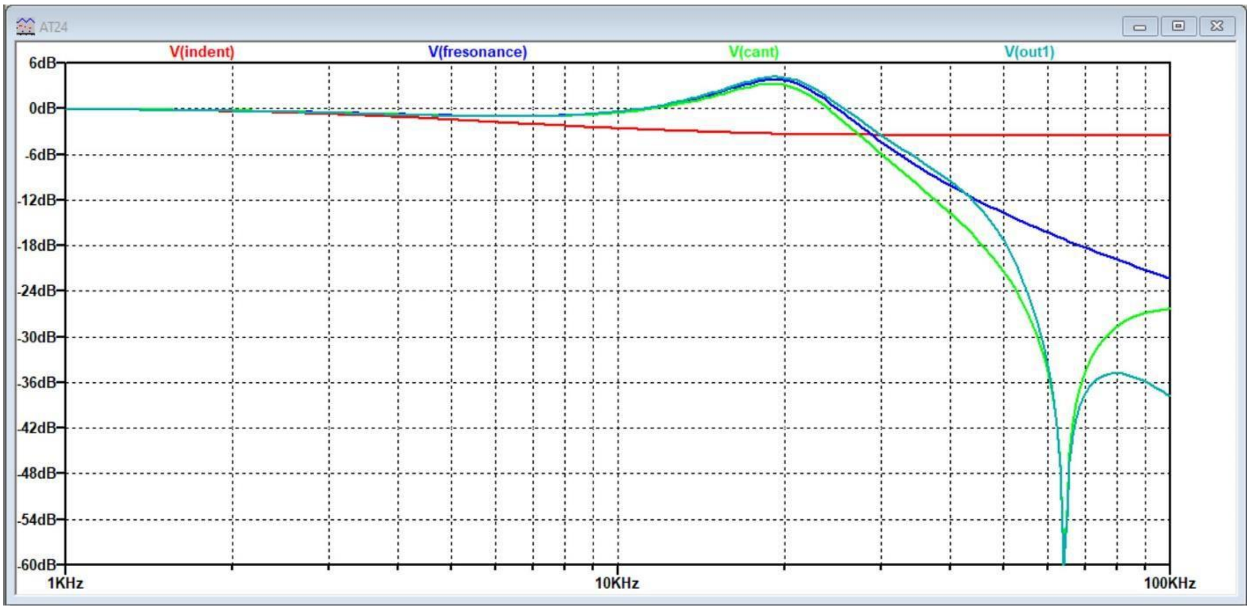


Figure 9, Frequency responses at various point from the AT24-Sapphires Circuit diagram

To test the thesis that the Cantilever doesn't see the Generator, because of the very weak coupling, a different load of 7K1 instead of 48K5 was recorded and at the same time simulated with the complete replacement diagram in LTSpice.

Result when projecting the various curves In one image on top of each other, shows a perfect confirmation for the thesis in figure 10.
So, the electrical model with two independent circuit diagrams for Cart assembly and Generator can successfully predict the FR with all sorts of termination load.

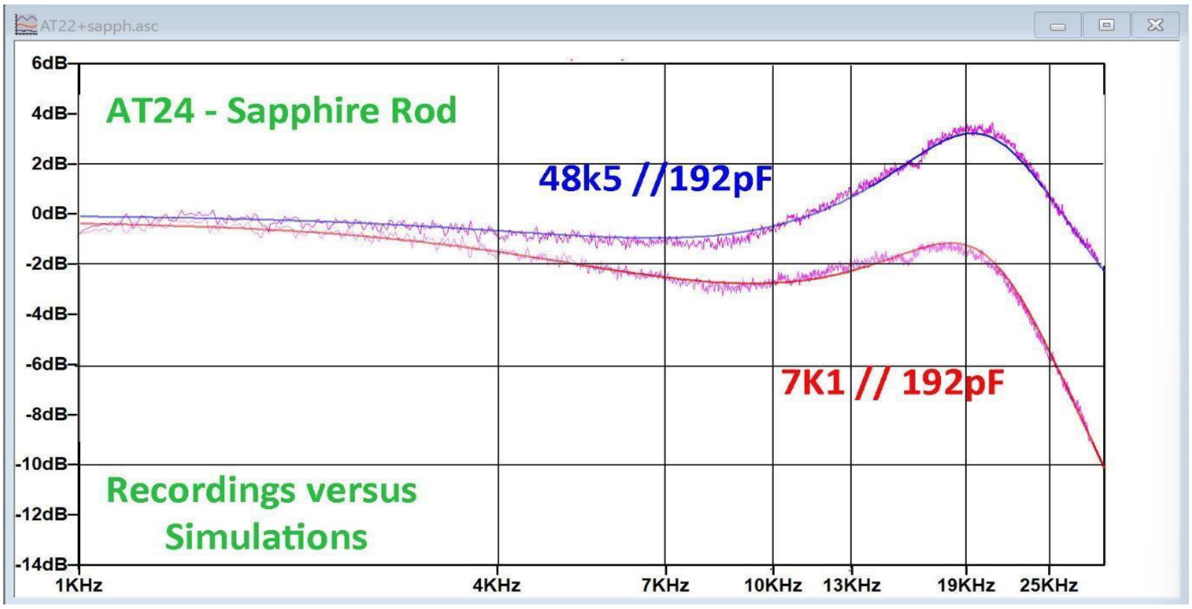


Figure 10, Recorded and simulated FR for two very different load situations

And here results for two more Carts, performing the same tests comparing recordings to the LTSpice replacement diagram, resp a AT22 with ATN23 Beryllium cantilever and 6um Shibata tip, and a AT150 with ATN152 Beryllium cantilever with a 5um Shibata tip, having two completely different Generators.

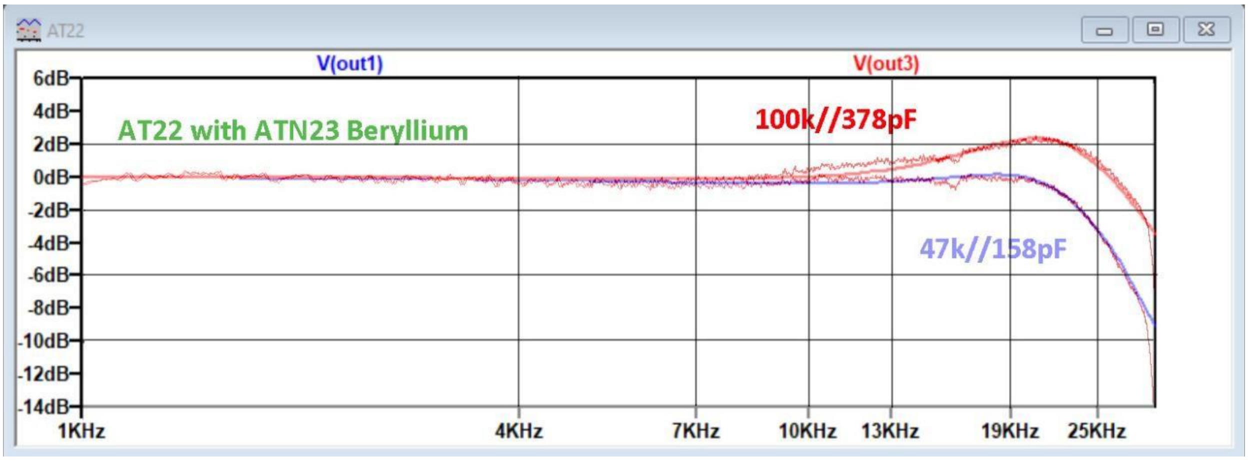


Figure 11, Recording versus simulation for a AT22 with ATN23 Cantilever

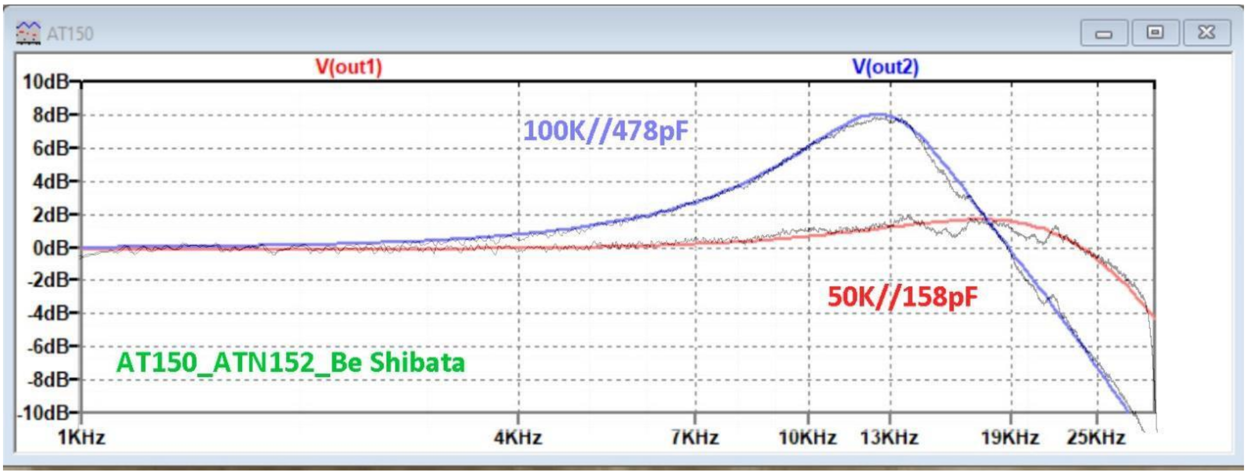


Figure 12, Recording versus simulation for a AT150 with ATN152 Cantilever

Whilst this is a limited number of tests, the match between simulation and measurement is close enough that we may conclude that this demonstrates that the generators and cantilever are isolated and cannot directly affect each other. This also implies that DC running through the Cart will in no way influence the Cantilever’s behavior as is sometimes mentioned and damping of the cantilever by loading cannot work

5) Terminating the Cart with a load much smaller as 47K (Damped Loading)

In fig. 1, upper right corner, the FR with an alternative load was simulated, in this case causing a 75µsec pole with Lcart plus Rcart. Any Rload could be used, but using a load creating this 75µsec pole has the advantage that T3 from the Riaa network can be switched off, keeping the Riaa preamp still available to be used for full Riaa use when switched back in position again. Damped loading mode or regular Riaa mode with at the flick of a switch.
In the sims below applying this 75µsec pole, T3 is switched off in the Riaa Amp.

With a simple Cart model only consisting of Lcart and Rcart, one gets the impression that the FR is largely extended, mainly because the capacitive load that's in parallel to Rload, is contributing to a significant lesser amount.

Figure 13, The effect of 75usec damped loading on a simple Cart model

With a bit more detailed circuit diagram is in fig. 1, this extension in FR is still very present although in that case another pole has to be added to flatten the FR.

But now that we have the complete circuit diagram from Cantilever plus Generator, it's now possible to look at the overall FR

First Cart to use is the AT24 with Sapphire Cantilever from replacement diagram fig 8.
Because a very low Lcart of 83.5mH and Rcart of 232R, we need a Rload=880R for a75µsec pole.

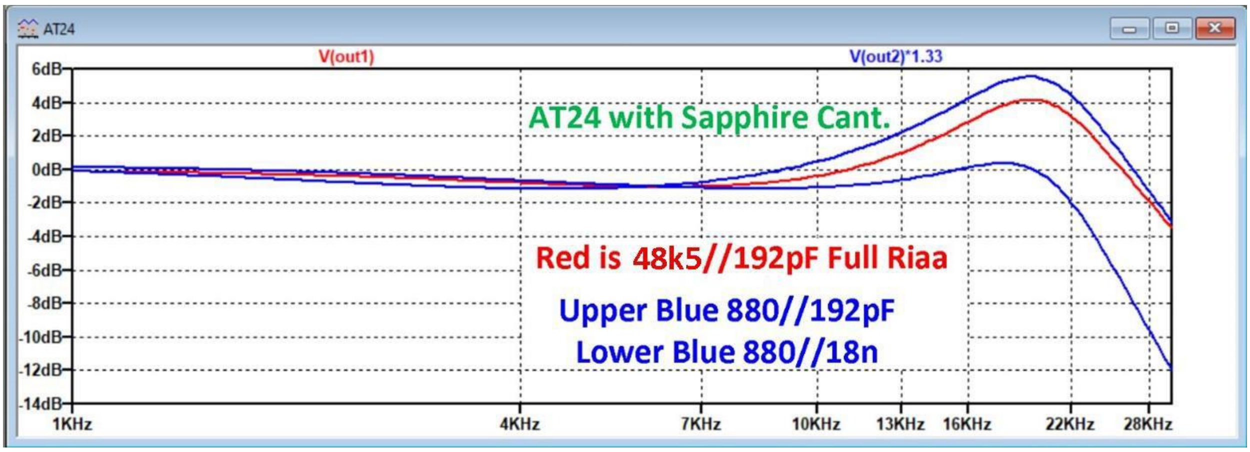


Figure 14, Loading the Cart with a 75µsec pole versus 48K5//192pF full Riaa

When just applying this 75µsec pole, the resonance peak at 20Khz even got 1,5dB higher without any further improvement while at the same time output was reduced by 2.5dB, just because of the added 880R load.
To reduce resonance, 18nF was added in parallel to the Rload creating a 14µsec pole.
This flattened the response quite a bit, although the FR wasn't extended at all as was the case with the simple model or with the Generator only. This generator was not a good fit for damped loading.

So, let's try the AT150 with ATN152 from figure 12.
Here's the replacement circuit diagram with fc at 68Khz for the 45rpm disc at 16.5 cm diam.

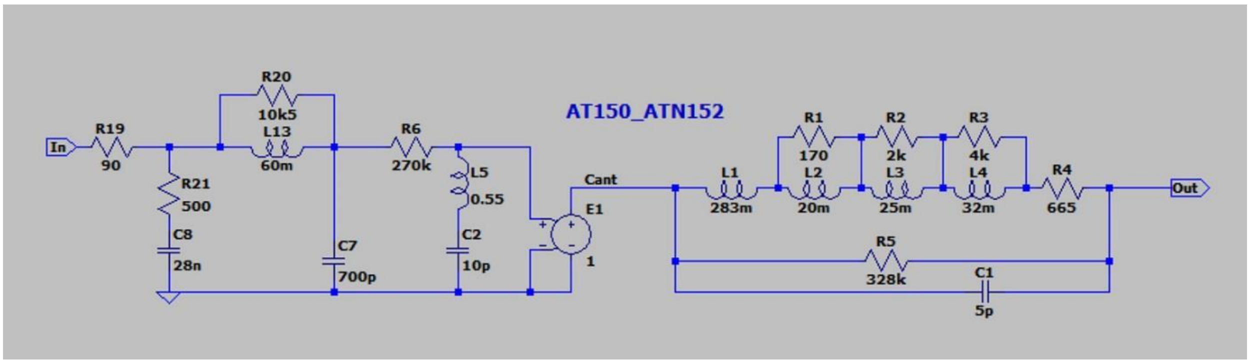


Figure 15, Replacement diagram for the AT150 with 5µm ATN152 Beryllium Shibata tip.

This Cart demands a very low capacitive load. In this case 100pF was used, already a very low value for interlink, TT and preamp together, less is not realistic.
With Lcart = 315mH and Rcart = 665R, a 3k5 load resistance would be expected for a 75µsec load. However, seeing the immediate result in the sim, it turned out that 3k7 was a slightly better choice.
But as before with the AT24, an additional at 8µsec pole was still needed to flatten the response, in this case 2n2.

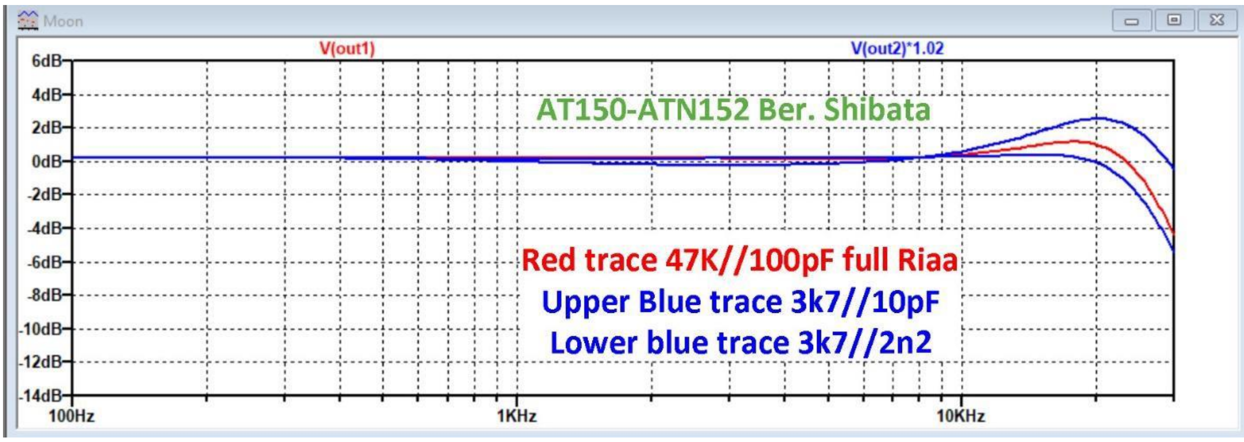


Figure 16, loading the Cart with a 75µsec pole versus 47k//100pF full Riaa

There is just another thing noticeable: The dip at 5Khz can be lifted when damping the resonance at 20Khz. This is what happens when adding the 2n2 cap, but also with the full Riaa version when using 100pF, although in fig 14 this Indent part, composed of R19,R21 and C8 is doing its job.
But in the end, the effect of the 75µsec pole is again not extending the FR as was expected from the simple model in fig 13.

The last thing to compare between both termination versions was to look at the impulse response. With the simplistic Lcart and Rcart version, impulse response is much better, although this doesn't automatically mean a better sound.
However applying a square wave to the complete replacement diagram, things are again looking different from expectation.

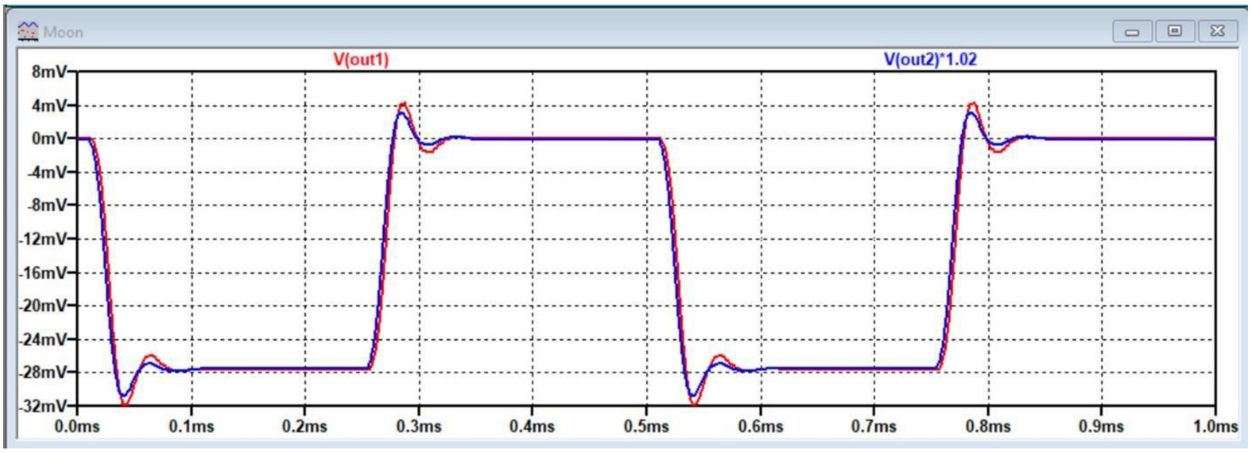


Figure 17, Square wave on AT150_ATN152 with 47k//100p full Riaa and 3K7//2n2 minus T3

Hardly any benefit can be found for the 75µsec pole loading in blue compared to the 47K//100pF full Riaa version in red.
For a number of different Carts these test where repeated, but results were not at all encouraging towards the use of this type of loading.
At least in all cases, an extra pole had to be added in the form of a cap in parallel to Rload.

With a lower Rload, two extra things will happen, I) a lower gain and II) as a direct consequence a lower S/N ratio.
However with the current low noise op-amps there are enough models available that will keep S/N at acceptable levels, keeping the noise still low enough below the LP's surface noise.
Using electrical "cooling" to improve S/N therefore is only making things more complex.
On average some 3dB loss in S/N can be expected with the 75µsec load pole.

The conclusion has to be that damped loading such as in Aurak and Vinyltrak [6] topologies, seems only beneficial in very special cases and have to be used with great care. Simple models promising an extended FR don't hold in real life. And as we have seen, the electrical roll off is nearly always well controlled with 47K, where the very important load capacity has to be selected for the flattest possible FR.

6) **Comparing the model in this paper to another model.**

Now back to an often quoted model, amongst others used by van Maanen [2] and van Raalte [3], the assumption being that the Cantilever system, in this case a Stanton 681EE, is resonating with a high Q, resulting in a peak of almost 13dB, and that this peak has to be addressed with a Generator having much narrower FR.
The result of both visible in figure 18 below.

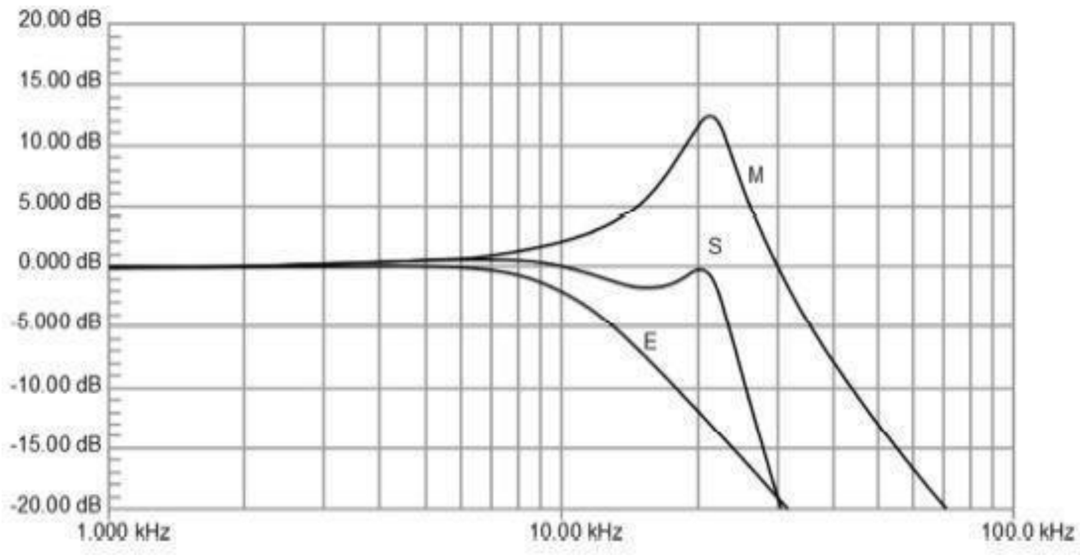


Figure 18, One of the models circulating in audio land.

Looking at figure 3 and figure 4, the opposite seems to be true, the tip/cantilever assembly's resonance peak is at a much lower level, in case of these four Carts between +2dB and -2dB, and the Generator has a FR exceeding the Cantilever's one instead of being narrower.

But as can be seen in figure 7, all assemblies will have a resonance caused by L1 and C2 damped by R3 even for the highly damped Denon DL-107. For the highest and lowest Fres of the Carts tested these resonance frequencies where at resp:
AT24-Sapphire 19.35kHz
DL-107 8.43kHz.

As a matter of fact, not being part of this paper, but Indentation, LP-Tip Resonance and Cutoff can also be seen with MC cartridges..

7) Further areas for research

We believe that in this paper a new and more accurate model for analyzing cartridge behavior has been generated; however it would be nice to look in more detail at some aspects if we can develop the needed test methodology.

Firstly we have used a model for stylus/vinyl resonance. In the cantilever's FR the contribution of the cantilever's rod is included. Since we have several comparable cartridges with different rod materials from Aluminum to Beryllium.
It would be nice if we could confirm that different rod materials are making a difference in overall FR.

Secondly we have as yet been unable to confirm the used model for Fc. This should be testable if we have multiple identical cantilevers with different size tips on and examples of these same styli on different cantilever materials.

8) Consulted literature:

[1] Equivalent circuit of a phono cartridge (pspatialaudio.com)

[2] H.R.E. van Maanen, "Compensatie van Mechanische Resonantie bij Pick-up Elementen", Radio Elektronica 79, 15/16, pp. 25-29 and 17, pp. 35-41 (1979), in Dutch. (download: http://www.temporalcoherence.nl/docs/MERK1979.pdf)

[3] Correcting Transducer Response with an Inverse Resonance Filter A biquad filter based on the Sallen-Key filter topology by Steven van Raalte, as published in Linear Audio.

[4] Factors Affecting the Stylus/Groove Relationship in Phonograph Playback Systems C. R. Bastiaans. AES paper.

[5] Equivalent mass, fact or fiction. Audio, march 78. Roger Anderson, Shure Brothers Inc.

[6] VinylTrak – A full featured MM/MC phono preamp, Bob Cordell, linear Audio volume 4