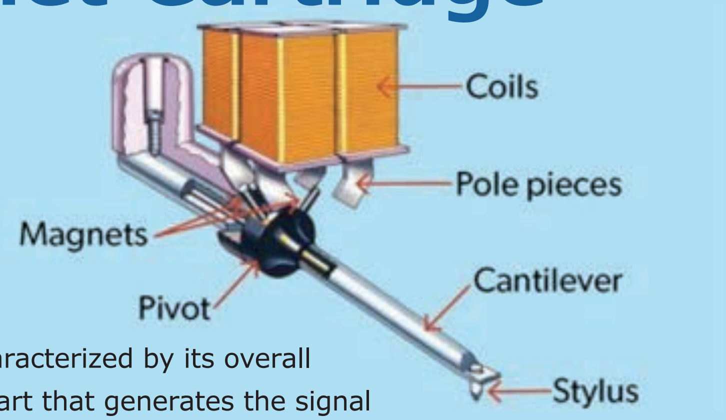
Individual Transfer Curves of Moving Magnet Cartridge Subassemblies



By
Hans Polak

A moving magnet (MM) phono cartridge can be characterized by its overall transfer function. But the transfer function of the part that generates the signal through magnetic induction has its own transfer function, which can also be measured. By translating the latter into an equivalent electronic circuit, further insight and possibilities for optimization can be obtained. Hans Polak explains.

A moving magnet (MM) cartridge can be considered as composed of two important parts, a (removable) Cantilever Assembly complete with stylus, suspension, and attached magnets and a Voltage Generator receiving the cantilevers signal through magnetic induction, hereafter indicated as generator. The overall frequency response or transfer curve (TC) for the complete MM cartridge can be recorded for several load schemes with calibrated test disks; let's call this transfer

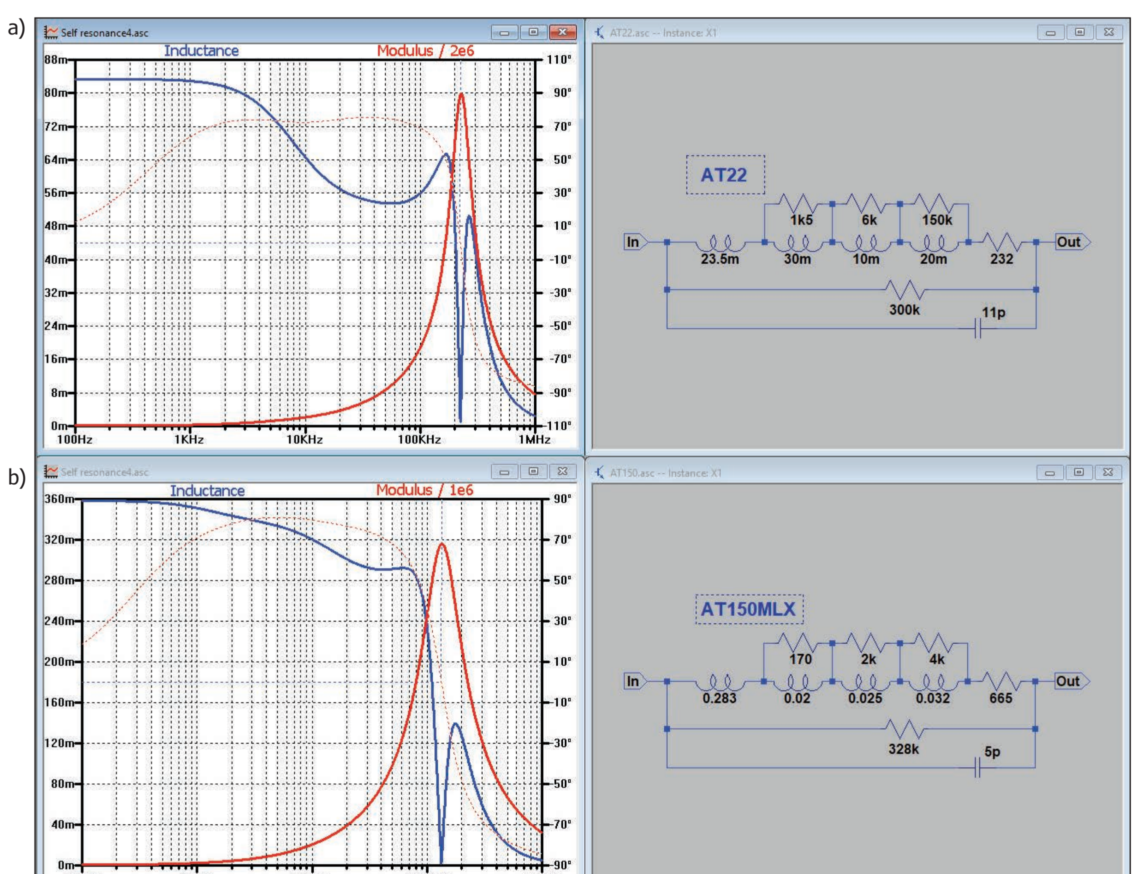


Figure 1: Circuit diagram for the Audio Technica AT22 (a) and AT150MLX (b).

function FR1. Its voltage generator's electrical properties can also be measured with a Vector Network Analyzer (VNA), accurately up to several megahertz, also resulting in a TC; let's call that FR2. Subtracting FR2 from FR1 will result in the TC of the cantilever assembly FR3. By translating FR3 into an electrical equivalent diagram, it will be possible to further investigate this TC and understand the factors leading to its properties.

With all the input of the noted measurements, the goal of this article is to find out whether the mechanical and the electrical part are "seeing" each other or can be regarded as independently operating parts.

Equivalent Diagrams for MM Cartridge Generators

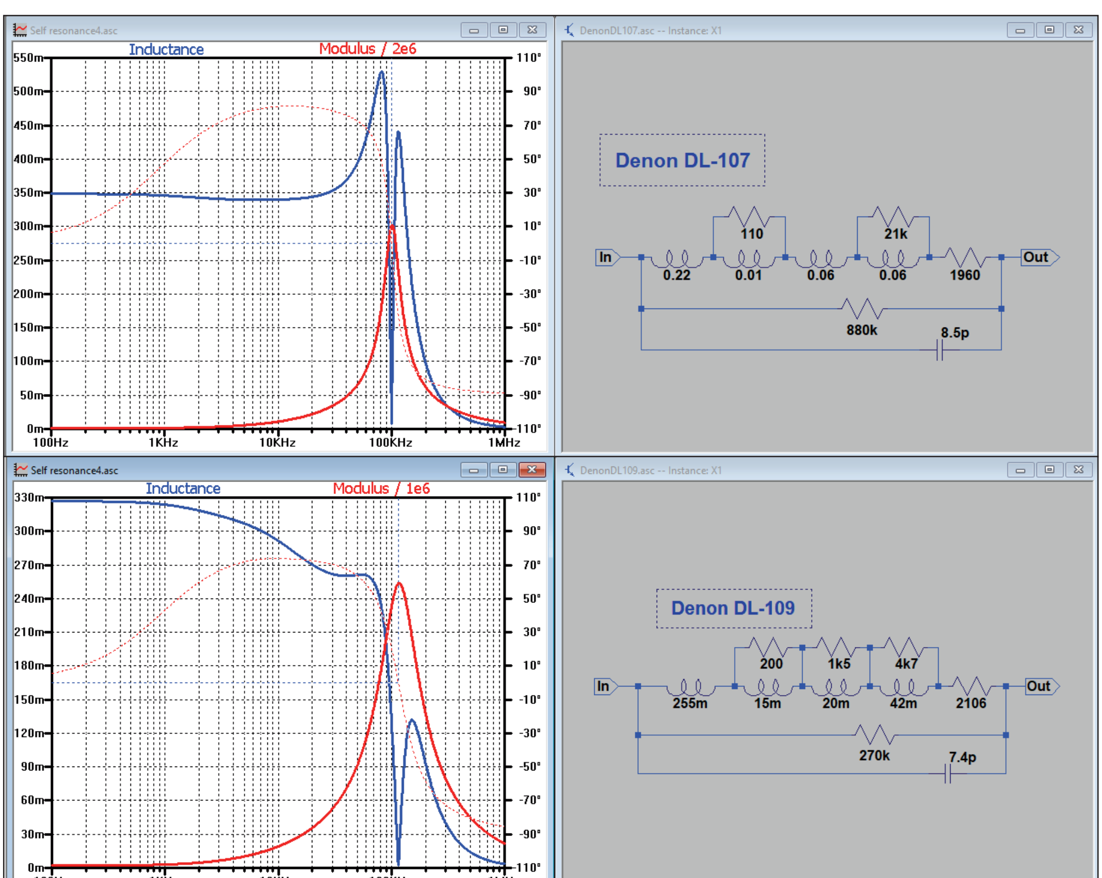
Factory specifications for cartridges, particularly inductance and resistance values, are generally inaccurate and too simplified to be used here. As an example, the official factory specifications for the AT150MLX are 3200Ω (1kHz) and 320mH (1kHz), figures that provide only limited information, which is not very useful for our purpose.

Therefore, in making a correct model for the generator part of the cartridge, the first step is using an instrument called a VNA. This is where the whole exercise started. Bill Shurvington, having a large collection of all sorts of cartridges, made available eight totally different cartridge detailed measurements of their generator properties. The circuit diagrams for the cartridges are shown in **Figures 1-4**: the AT22 and the AT150MLX (Figure 1); the Denon DL-107 and the DL-109 (Figure 2); the Ortofon 40 and the Ortofon S-120 (Figure 3); and the Ortofon Super OM10 and the Technics 205-IIX (Figure 4). The VNA produced all the needed parameters such as inductance, capacitance, and impedance with corresponding phase behavior versus frequency from 100Hz to 1MHz.

The next step was to find the generator's electrical equivalent model producing exactly the response FR2 that was measured with the VNA. For this purpose, a powerful simulation program called LTspice from Analog Devices was used. By meticulously trying to replicate their measured values, the various circuit diagrams emerged.

Subconclusion 1

What resulted is that all cartridges could be represented by the same generic diagram. It also became apparent that it made no difference



a)

b)

Figure 2: Circuit diagram for the Denon DL-107 (a) and the DL-109 (b).

a)

b)

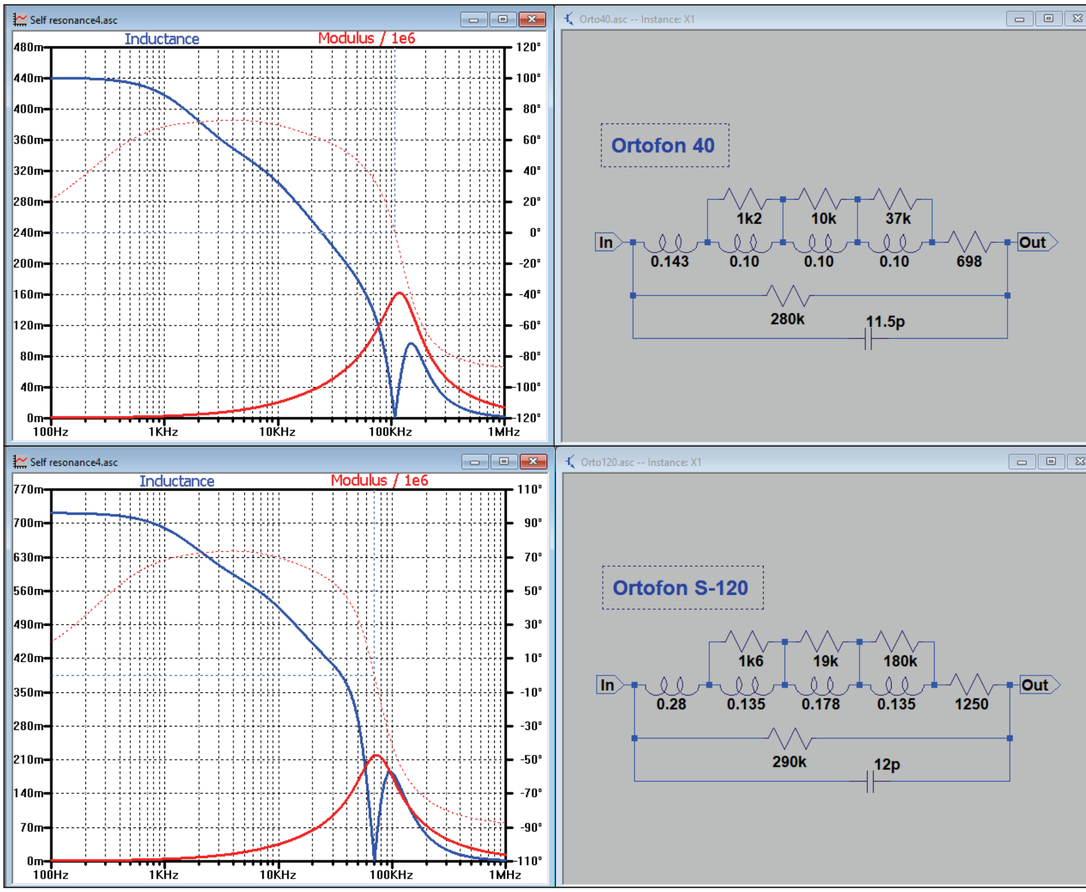


Figure 3: Circuit diagram for the Ortofon 40 (a) and the Ortofon S-120 (b).

a)

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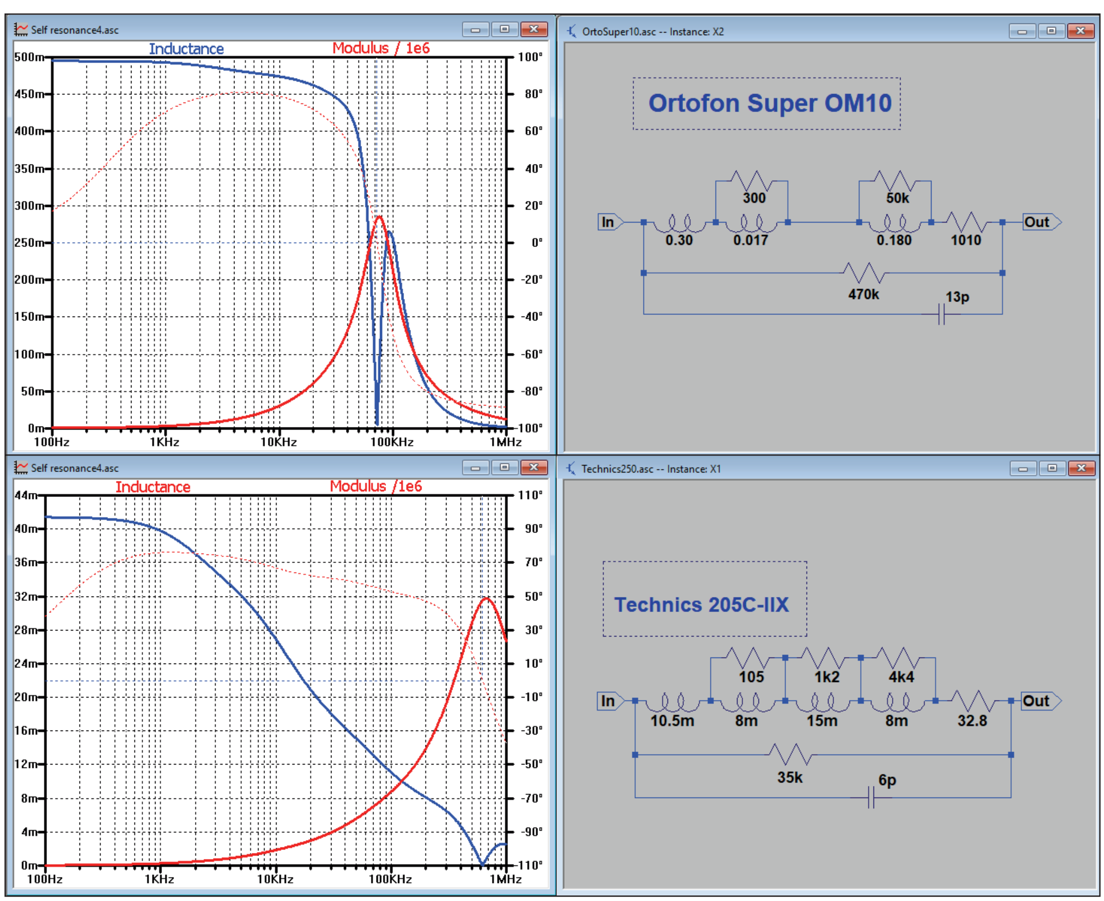

Figure 4: Circuit diagram for the Ortofon Super OM10 (a) and the Technics 205-IIX (b).

whether the cantilever assembly was attached to its cartridge-body or not, not even in the tiniest details, although the VNA measured up to 10MHz with very high accuracy. So, the generator doesn't "see" the presence of the cantilever assembly: One can put a signal on a cartridge's output pins, but that will never lead to a moving tip. The next 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?).

Measuring a Cartridge Frequency Response with a Test Disk

One problem in measuring cartridge frequency responses is to find a suitable test record. Many of those from the "golden era" of vinyl have potential anomalies that skew results. For this test we used a RIAA corrected pink noise recording going from 500Hz to 30kHz on a 45rpm disk from CH Precision. The recorded noise was computer generated, providing an accuracy that is rare to find on a test record. Pink noise has equal energy per octave, and when displaying the frequency response (FR) with a FFT spectrum analyzer, it will have a negative slope of 10dB/decade.

To verify the correctness of the recorded signal, the record was played back with a Benz LP MC cartridge, whose FR is specified from 10Hz-50Khz within 1dB. **Figure 5** seems to fully confirm that this disk can be used as a reference for our purpose. Up to 28.5kHz the response is within ±0.5dB.

To get an even better view on the spectrum,

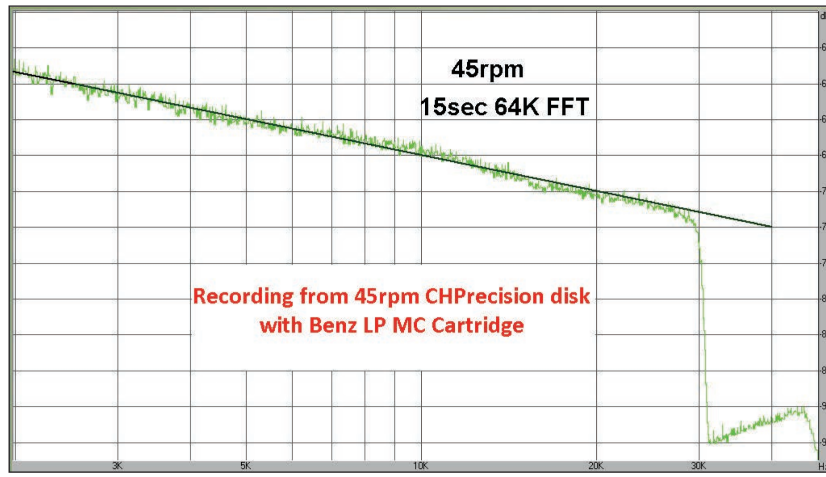

Figure 5: Checking the test signal on the CH Precision test disk.

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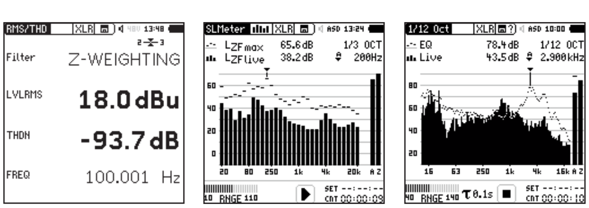

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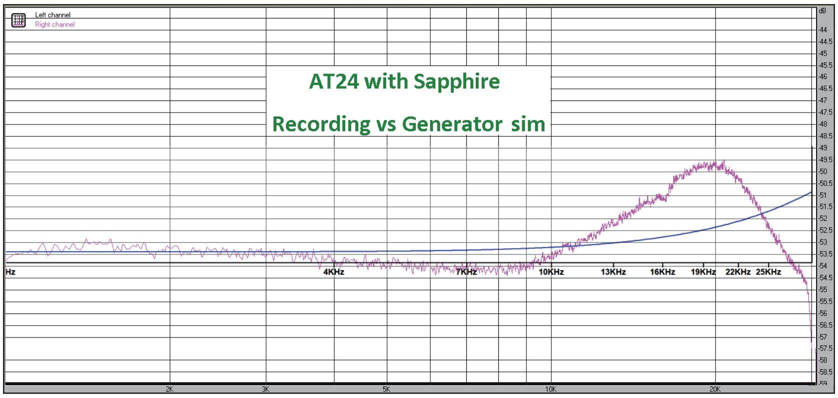


Figure 6: FR1 recorded with AT24 together with the FR2 simulated for its Generator, both terminated with 48.5kΩ (48k5) in parallel with 192pF.

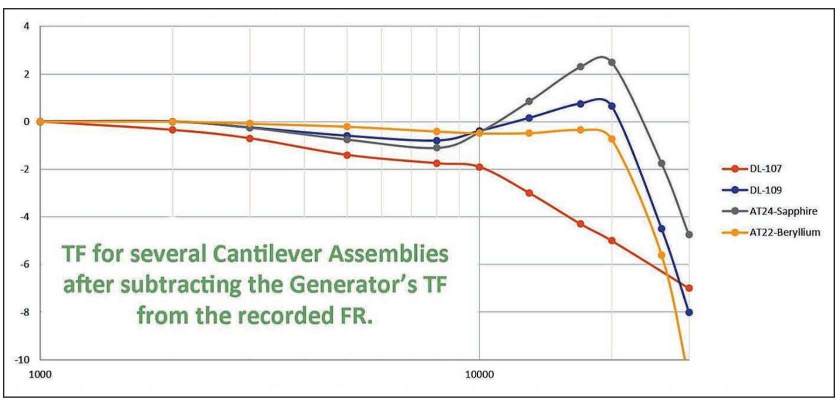
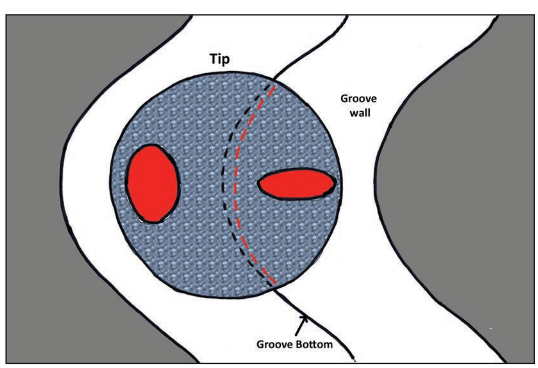


Figure 7: Transfer curves for four cantilever assemblies.

Figure 8: The shortcut the tip takes because of indentation.



Mathematical Background

For the resonance frequency fr between tip/cantilever and vinyl, the mathematical relation is:

$$fr = [0.636/\pi Sqrt(m)]*(E0^2 FvR)^{1/6},$$

where m is the equivalent tip mass; Eo is the the Young modulus, 3.76e9 N/m² for vinyl; Fv is the stylus force (assumed 2 gram); and R is the tip radius touching the track wall.

For the cutoff frequency fc we obtain the equation:

$$fc = 1.51(V/\pi)*(E0/FvR)^{1/3}$$

where V is the track speed. fc is inversely proportional to $Fv^{-1/3}$; the higher the stylus force, the lower fc. The Q of fc is 0.88.

the recorded frequency response FR1 was rotated by multiplying it with an upgoing 10dB/dec slope. This facilitates comparing it 1:1 to FR2 generated by the simulated generator model.

The first cartridge measured on the CH Precision test disk was an AT24, having the same generator as the AT22, equipped with a custom sapphire cantilever assembly. This assembly with a higher moving mass than fitted on the factory cartridge was chosen to amplify any mechanical anomalies. **Figure 6** shows in purple the FR of the recording made on the test record, here displayed together with the generators FR simulated in LTspice in blue, both on exactly the same scale. So, because the cantilever assembly is adding its TC to the generator FR, the difference between the two will be caused by the cantilever assembly TC.

Determining the Cantilever Assembly Transfer Curve

So, to find the assembly's FR3, the next step had to be to subtract both curves, the generator FR2 from the recorded FR1. Neglecting the small dip at around 16kHz in Figure 5 and Figure 6, that turned out to be disk related, the TC for the cantilever could now be determined up to 30kHz.

Doing the same exercise for an AT22 with the OEM Beryllium cantilever and for a Denon DL-107 and a Denon DL-109 resulted in the TC for four cantilever assemblies (**Figure 7**).

Note that the AT-22 was a high-end MM from the late 1970s 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.

Constructing a Model for the Cantilever Assembly

With the gathered data, an electrical analogy can now be constructed describing all four models, preferably with one and the same topology by just changing component values. For this, several factors can already be considered. 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 become deeper from acceleration forces in the concave or the tip pushing part as opposed to the force and indentation of the sine wave convex part. Therefore, the tip does not follow 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 cartridges are showing in their TC somewhere between 5kHz and 10kHz.

In **Figure 8**, 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 cartridge 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 further indentation to come to a halt as from a certain frequency.

However, when frequency increases, a stylus/groove resonance frequency causes the cartridge output to increase; again, like any non-critically dampened mass spring system. In this case, it depends on tip mass, vinyl properties, stylus force, and tip radius. Resonance frequency is weakly proportional to stylus force, the higher the stylus force, the higher the resonance frequency, independent of track speed. Making the stylus force twice as high results in an increase of resonance frequency of 1.12 times. See the section "Mathematical Background" for the full derivation of the transfer function.

There is a third mechanism called fc, the cutoff frequency where the cartridge no longer produces 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. Increasing the frequency any further causes the mass to move in the opposite direction. This is what also happens between the vinyl "spring" and the tip mass, here dependent on track speed, vinyl properties, stylus force and tip radius. Fc is a more dynamic parameter depending on rpm and position on the vinyl record and is inversely proportional to the stylus force. With a stylus force two times as high, fc decreases by a factor 0.79. See the "Mathematical Background" section for the full derivation of the transfer function.

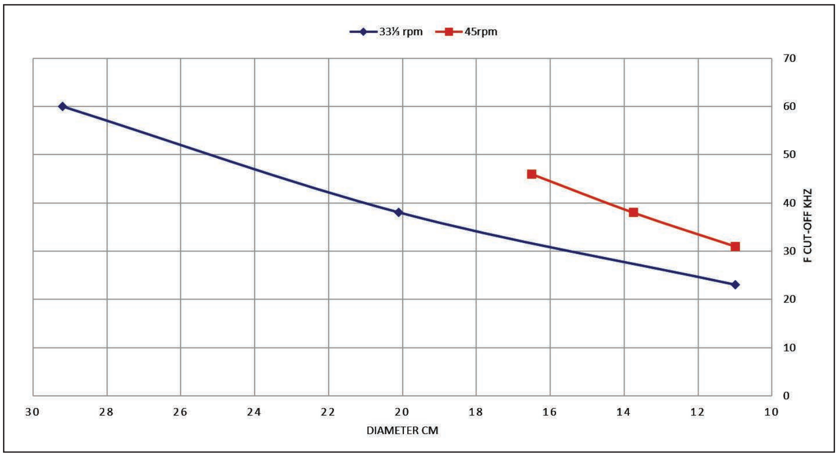


Figure 9: Cut-off frequency dependency on rpm and position for a 0.65 mil round tip.

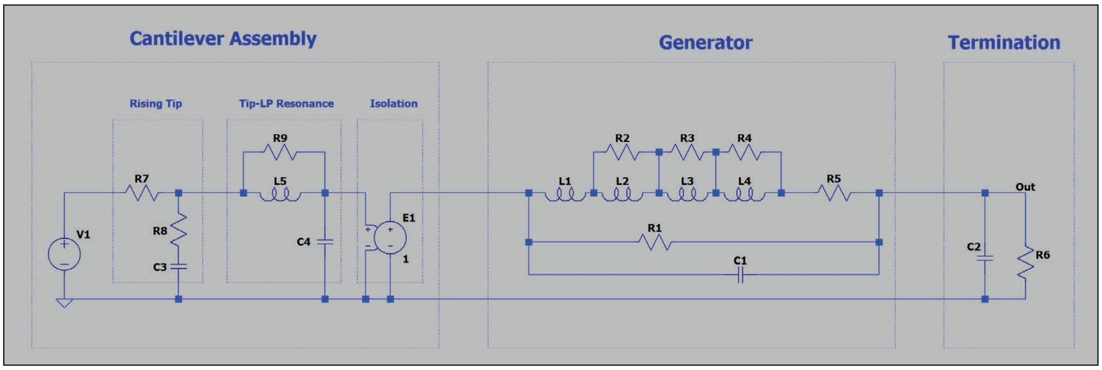


Figure 10: Generic model for cartridge plus termination.

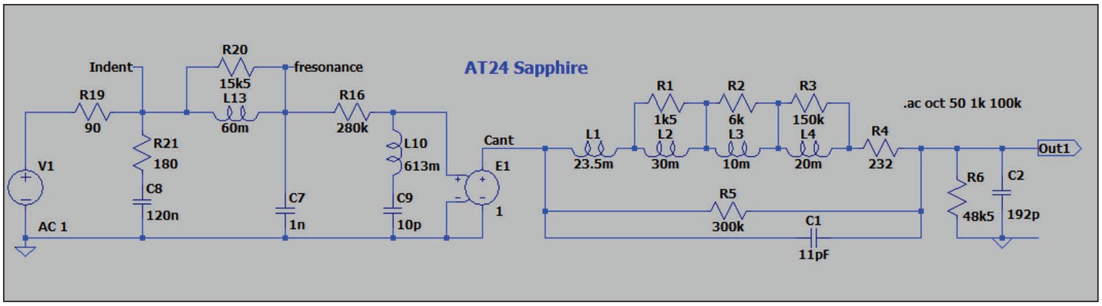


Figure 11: Circuit diagram for a AT24 with Sapphire cantilever and 0.24 mil elliptical tip.

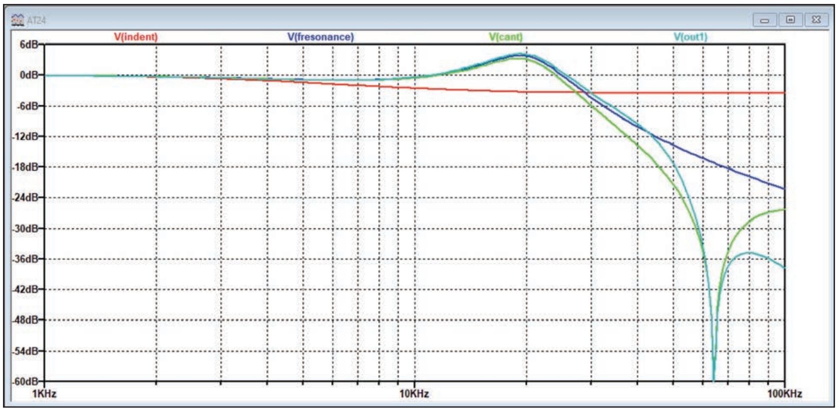


Figure 12: Frequency responses at various points from the AT24-Sapphire's circuit diagram.

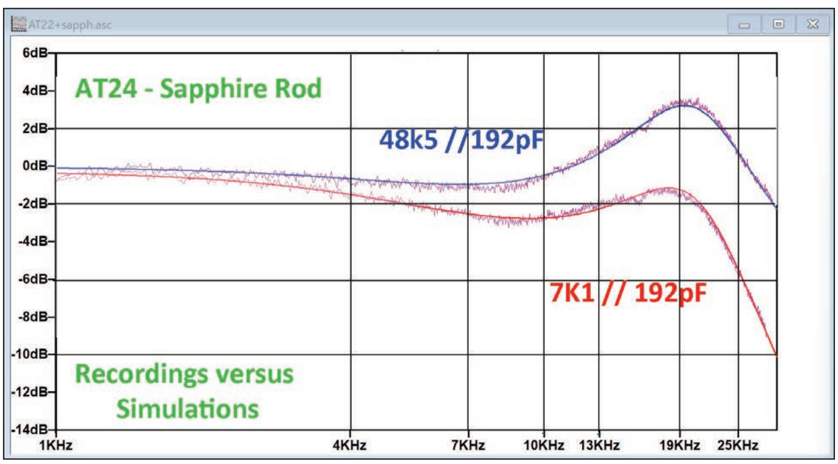


Figure 13: Recorded and simulated FR for two very different load situations.

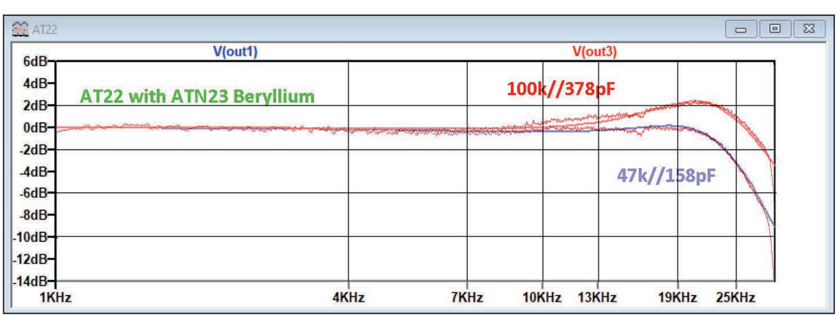


Figure 14: Recording versus simulation for a AT22 with ATN23 Cantilever.

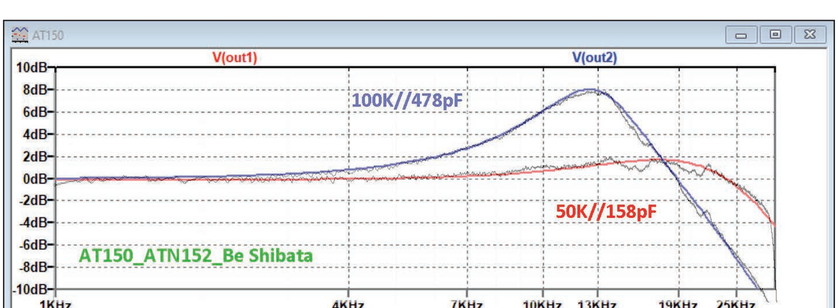


Figure 15: Recording versus simulation for a AT150 with ATN152 Cantilever.

In our test we used a 45rpm disc at 16.5cm diameter, causing fc to be 46kHz for a 0.65 mil round tip. To show the huge dependency on rpm and position on the record for this tip, see **Figure 9**, with fc going from 60kHz to almost 20kHz. In contrast, for a 5µm Shibata tip you can multiply all fc values by 1.5.

Adding together the results of these findings, we can construct a generic equivalent model for cantilever, generator, and termination, as shown in **Figure 10**. There are other models found in other papers [1], but none of them were able to match the tested cartridges from Figure 7.

Entering the correct components for the AT24 with a sapphire cantilever into this generic equivalent diagram, gives exactly the same overall frequency response as the recorded one, just because it was constructed that way by subtracting the generator FR from the recorded FR. With a 0.24mil elliptical mil tip, fc was 64kH at the position on the 45rpm record that was used. This results in the circuit diagram of **Figure 11**.

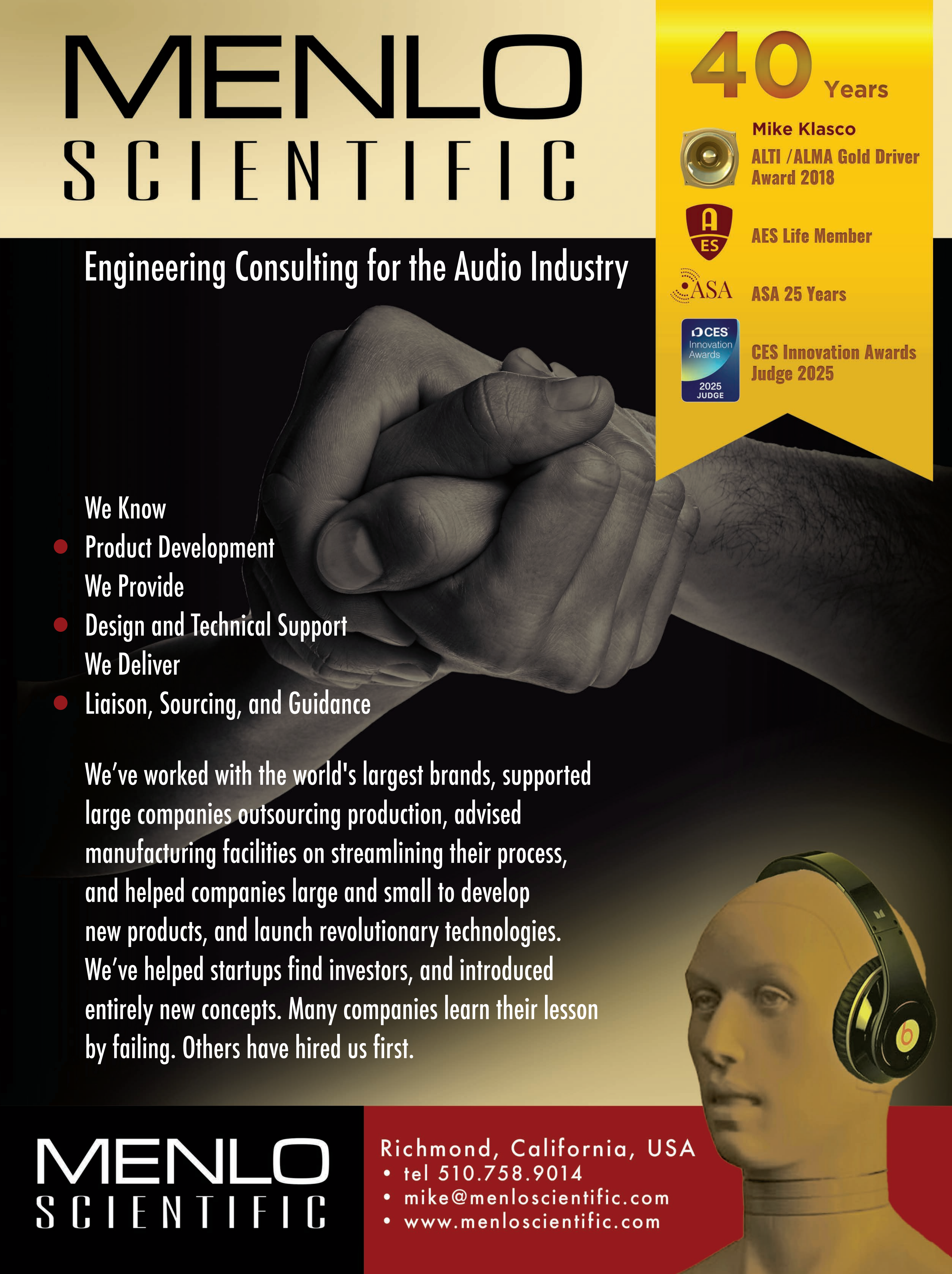
Frequency responses are shown in **Figure 12** for respectively record indentation in red, tip-LP resonance in blue, cutoff in green and the resulting overall response in teal. To test the thesis that the cantilever doesn't "see" the generator, because of the very weak coupling, both a recording was made and a simulation performed with the Figure 11 equivalent circuit, with a different load of 7.1kΩ (7k1) instead of 48.5kΩ (48k5). When projecting the various curves in one image on top of each other, the perfect conformance as seen in **Figure 13** is obtained.

Subconclusion 2

The electrical model with two independent circuit diagrams for cartridge assembly and generator can successfully predict the FR with all sorts of load terminations. **Figure 14** and **Figure 15** show the same results for two more cartridges, an AT22 with ATN23 Beryllium cantilever and 6µm Shibata tip, and an AT150 with ATN152 Beryllium cantilever with a 5µm Shibata tip, having two completely different generators. Despite the limited number of tests, the match between simulation and measurement is close enough that we may conclude that this demonstrates that generator and cantilever are isolated and will not affect each other.

Subconclusion 3

This implies that DC running through the cartridge will in no way influence the cantilever behavior as is sometimes mentioned, because of supposedly putting the cantilever under stress.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Comparison to Other Models

Now we will consider another model which is often referenced by for instance H. R. E. van Maanen [2] and Steven van Raalte [3]. In these articles, the assumption is 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 must be addressed with a generator having much narrower FR. This results in curves as shown in **Figure 16**.

Looking at Figure 6 and Figure 7, the opposite seems to be true; the tip/cantilever assembly resonance peak is at a much lower level, in this case between +2dB and -2dB, and the generator has a FR exceeding the cantilever one's instead of being narrower. But as can be seen in Figure 10, 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 resonance frequency of the tested cartridges these resonance frequencies were at 19.35kHz for the AT24-Sapphire and at 8.43kHz for the DL-107.

Although not being addressed in detail in this article, indentation, LP-Tip resonance and cutoff can also be seen with MC cartridges following the same path, whereby most MC generators are much simpler and can be represented by just a coil in the low microhenry (μH) range and a series resistance Rser mostly rather below 50R. The simple fact that most MC cartridges can drive transimpedance preamps with zero input impedance with no loss in frequency response, is just another indirect proof that

References

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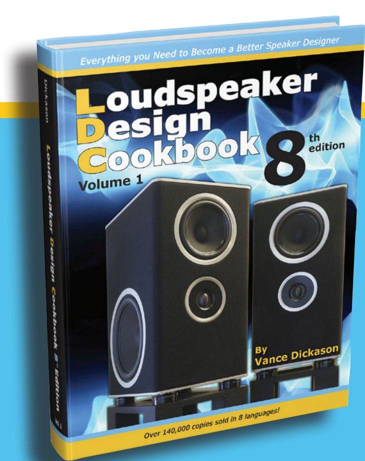

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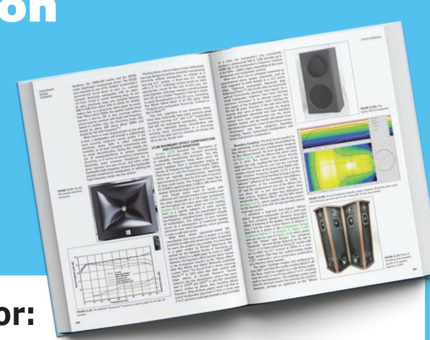

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the cartridge mechanical part does not "see" what termination has been used. However, the fact that experimenting with termination values of 10x Rser or higher can result in differences in sound perception, may well have to do with reflections within the interlink between MC cartridge and preamp, depending on the interlink characteristics.

Conclusion

In this article we have shown that the coupling between cantilever assembly and generator is so weak, that the interaction from one to the other or mutual feedback can be regarded as totally negligible. An often-referenced model of a resonating needle/ cantilever, electrically corrected by a generator with a much narrower FR, has been shown to be in error. The cantilever assembly model that came out of the investigation also gave new insights for a plausible explanation why many cartridges sag in their FR around 5kHz. The beauty of having an accurate model for the cantilever assembly plus generator is that all kinds of loads can be simulated to study their effect on the cartridge frequency response.

Author Acknowledgements: I would like to express my sincere thanks to Bill Shurvinton for making available a representative set of quite different Moving Magnet cartridges and to Dagfinn Rasmussen for making frequency response recordings with several MM cartridges under different load conditions. All this enabled me to do the technical analysis for this article.

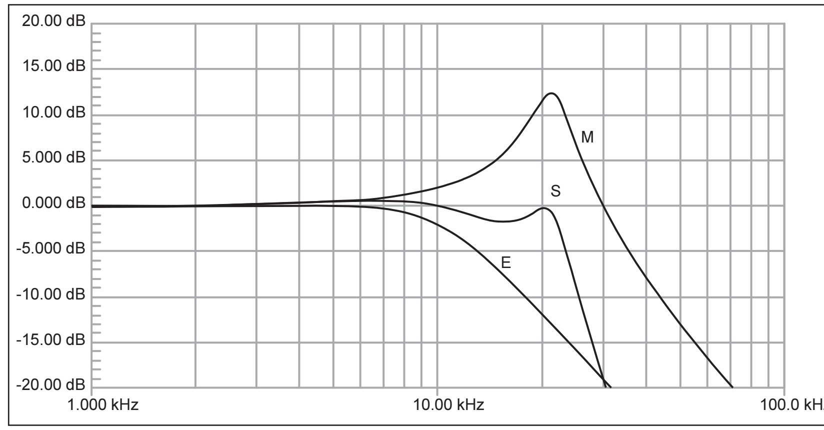

Figure 16: One of the models circulating in audio land. (Image Source: *Linear Audio*).

About the Author

Hans Polak started to study medicine after graduation but was quickly dissatisfied with the lack of technical focus. He switched to electronic engineering and received his MSEE in 1979. During his EE study he worked for a leading Dutch defence manufacturer, designing a chip for real time radar signal processing. After graduation, Hans founded the first Dutch computer manufacturing company, Holborn. Hard- and software were designed, developed, and manufactured in-house years prior to the IBM PC. The Holborn 6140 is on display at Amsterdam University's computer museum. When the IBM PC changed market dynamics, Hans started working with AutoCAD, becoming the biggest reseller/ distributor on the Dutch market. After having sold this company in the late 1980s, he has been active as investor, strategic advisor and business recovery specialist. After having listened to a pair of Quad electrostatics, audio became an important pursuit, initially improving high-end audio designs, later developing audio components from scratch. A series of his no-holds-barred Phono preamps were manufactured for a Dutch hi-end retailer and sold under the Allard Audio label as the absolute reference within their portfolio.

Cartridge Damping Loading

Terminating the cartridge with a load much smaller than 47k.

Using a termination load that creates a 75µsec pole has the advantage that T3 from the RIAA network can be switched out, allowing the preamp still to be used for full RIAA correction when switched back in again. Damped loading mode or regular RIAA mode with the flick of a switch! In the following simulations this 75µsec pole (= Lcart/ (Rcart+Rtermination), T3, is switched off in the RIAA amp.

With a simple cartridge model, only consisting of Lcart and Rcart, one gets the impression that the FR is extended, mainly because the capacitive load that's in parallel with Rload has much less impact (**Figure 1**).

But now that we have the complete circuit diagram from cantilever plus generator, it's possible to look at the overall FR. We will first look at the AT24 with a Sapphire Cantilever. Because this cartridge has a very low Lcart of 83.5mH and Rcart of 232R, we need an Rload=880R for a75µsec pole (**Figure 2**). When just applying this 75µsec pole, the resonance peak at 20kHz even got 1.5dB

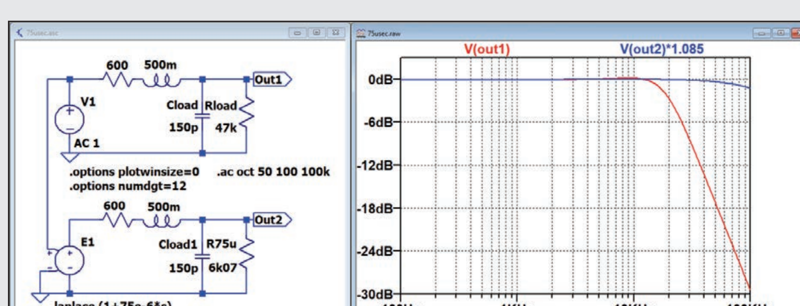

Figure 1: The effect of 75usec damped loading on a simple Cart model.

higher without any further improvement while at the same time output was reduced by 2.5dB, just because of the added 880R load. Because the levels were normalized at 1kHz, the reduction in level is not visible.

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 turns out not to be a good fit for damped loading.

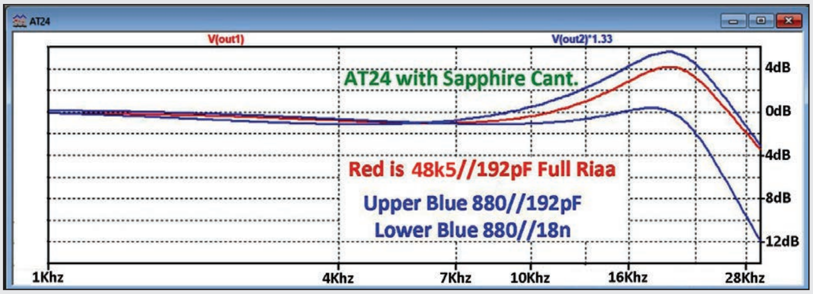

Figure 2: Loading the Cart with a 75µsec pole versus 48k5//192pF full RIAA.

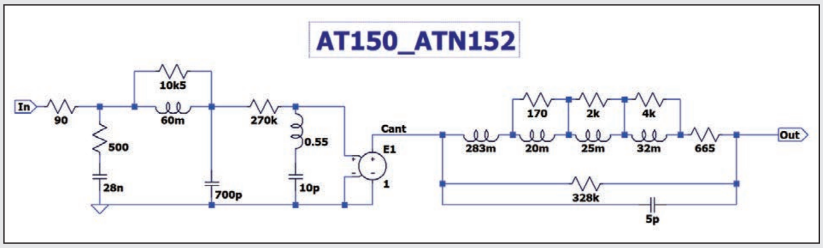

Figure 3: Equivalent diagram for the AT150 with 5µm ATN152 Beryllium Shibata tip.

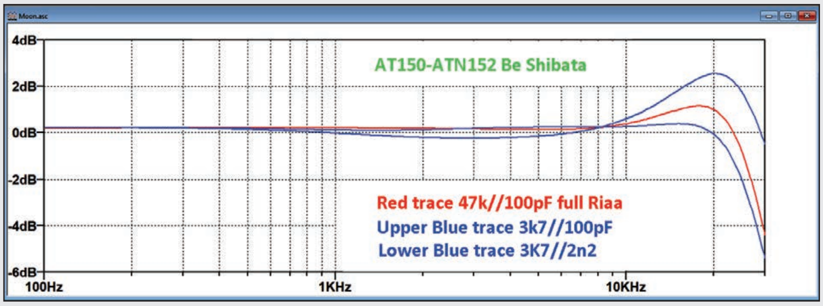

Figure 4: Loading the Cart with a 75µsec pole versus 47k//100pF full RIAA.

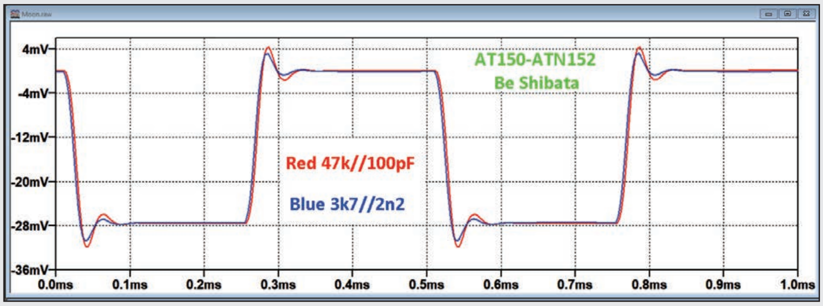

Figure 5: Square wave on AT150_ATN152 with 47k//100p full RIAA and 3k7//2.2nF minus T3.

So, let's try the AT150 with ATN152. Here's the equivalent circuit diagram for the 45rpm disc at 16.5cm diameter, giving an fc of 68Hz (**Figure 3**).

This cartridge requires a very low capacitive load. In this case 100pF was used, already a very low value for interlink, TT and preamp together, and it isn't realistic to expect a lower value. With Lcart = 315mH and Rcart = 665R, a 3.5kΩ load resistance would be expected for a 75µsec load. However, from the simulation, it turned out that 3.7kΩ 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 a 2.2nF capacitor (**Figure 4**).

There is just another thing noticeable: the dip at 5kHz will be lifted when adding the 2.2nF cap, but also with the full RIAA version when using 100pF where this composite part, composed of R19, R21 and C8, is doing its job. However, in the end, the addition of the 75µsec pole does not extend the FR as was expected from the simple model.

Finally, we looked at the difference in impulse response between the two versions. With the simplistic Lcart and Rcart version, the impulse response is much better, although this doesn't automatically mean a better sound. However, applying a square wave to the complete equivalent circuit described here, things are again looking different from what was expected (**Figure 5**).

Hardly any benefit can be seen for the 75µsec pole loading in blue compared to the 47k//100pF full RIAA version in red. For several different cartridges these tests were repeated, but results were not at all encouraging towards the use of this type of loading. 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 additional things will happen: a lower gain and, as a direct consequence, a lower signal/noise (S/N) ratio. However, there are currently many low noise op-amps 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 must be that damped loading such as in Aurak [6] and VinyTtrak [7] topologies, seems only beneficial in very special cases and must 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 the standard 47k load, where the very important load capacity must be selected for the flattest possible FR.