Resistor non-linearity – there's more to Ω than meets the eye

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Introduction

A good craftsman uses his skills not only in the design of his project, the use of tools and specialized knowledge but also has insight into the best parts for his goals.

In building audio circuitry, we may use computer modeling of the circuits under consideration, the latest test gear to measure the actual performance, and other modern tools to build our gear. But when we design a circuit we try to select the best components available for the task. The most common component is of course the resistor.

We know that resistors come in different values from a few thousandths of an ohm to tens of millions of ohms. They also come with wattage ratings from milliwatts to thousands of watts. There are also maximum voltage ratings; even though we may not exceed a power rating in use there will be limits on the maximum voltage across the resistor and even from the resistor to nearby grounded surfaces. Resistors also have temperature ratings. They may range from a change in resistance as low as 1 part per million of their initial resistance per degree C change in temperature to several thousand PPM/C changes. There are also changes in value with applied voltage. Most of this information is standardized and available from the manufacturers for their products.

The basic equation for resistors is Ohms Law I x R =E. This rule was based on the observation of how voltage and current are related. However as nothing is ever perfect there are always deviations from the rule.

I decided to do some tests to see how real resistors behave under conditions typical of audio circuitry.

Test circuit

The basic test principle is that Ohms law is linear. One ohm plus one ohm equals 2 ohms. If there is something causing distortion it will not be linear. If this is caused by a voltage across the resistor,

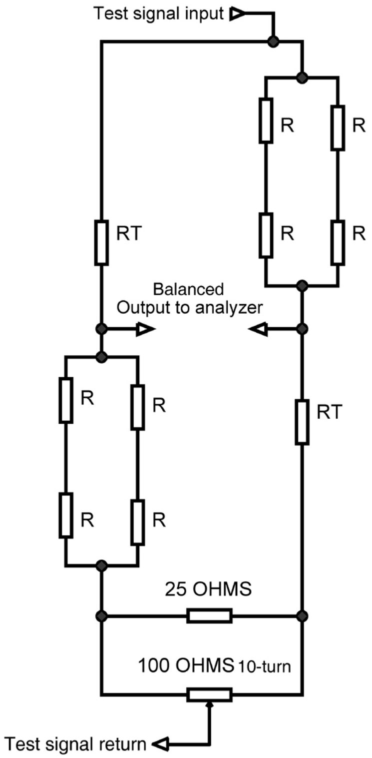

Figure 1. The Test Circuit.

the more the voltage the greater the distortion should be. The important characteristic is that since the distortion is not linear the distortion caused by one volt across the resistor is not twice (or half) the distortion caused if there were two volts across the same resistor!

This led me to the test circuit shown in figure 1.

In this circuit I can make all ten resistors (R, Rt) the exact same type and value. A signal provided to the input should be divided exactly by one half and there should be no output between the two matched voltage dividers! A small trim adjustment was made because even with matched resistors they will not all be exactly the same resistance. If there is some nonlinear distortion present then the groups of four resistors having only one half of the voltage across each unit will have less distortion. Because it is a nonlinear distortion it will not be exactly the same as what is across the single unit forming the other half of the voltage divider! So the distortion should cause a signal to appear across the output.

A quick test was done as shown in figure 2. Ten inexpensive ¼ watt metal film 1% resistors were used. A test signal of 1000 hertz was applied at a level of 15.81 volts. This would put 62.5 milliwatts across the single resistors or ¼ of their rated wattage. There are two tests shown here. One is with the 1000 hertz test signal nulled as much as possible (shown offset) and the other with much less suppression. A careful look shows that the third harmonic distortion hardly changed. For a greater than 60 db change in the null the second harmonic distortion changed by less than 5db. There also are quite a few artifacts from the ever present 60 Hz power line harmonics. I think these help provide the graphs with a reality double check.

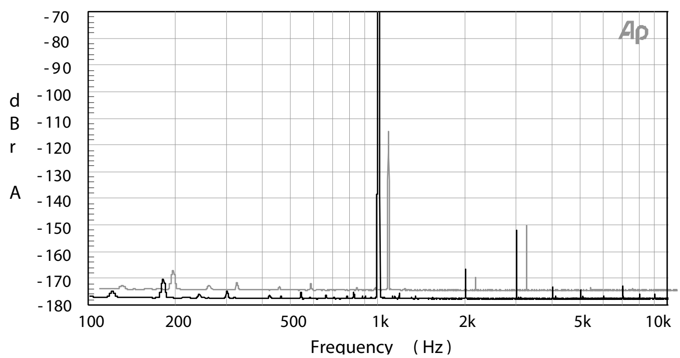

Figure 2 Proof of concept

Test results.

The question arose if the distortion was caused by self heating of the resistors. By changing the frequency of the test signal the heating time should change and so should the distortion.

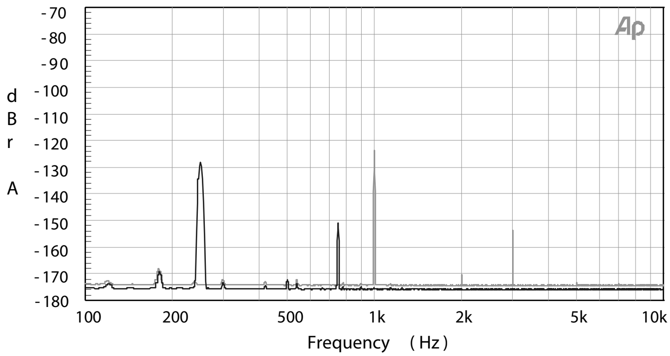

Figure 3 Distortion vs frequency

Figure 3 shows these tests. The higher frequency 1 kHz test had lower 3rd harmonic distortion. The next step was to determine what type of resistors had the lowest distortion. If I could find perfect resistors they could be used for the groups of four in the test circuit and I would only need to change the other two for a much simple testing method. Many audio experts prefer a Vishay S102K "Nude" resistor (TX2352). I used ten of these in my test setup and got the results shown in Figure 4.

These Vishay resistors also showed that distortion increases with level and decreases with frequency. A very important lesson is that a 6 db increase in level increases the distortion by 12 db! From fig 3 it appears that the frequency based increase is approximately by the square root of the frequency ratio. So one can now design for a distortion target if you know the frequencies of interest and the signal level. Higher values of resistance or higher wattage units should show less third harmonic distortion, the limit for the use of these resistors at high values would probably be thermal noise.

I also decided to try some Dale RN65 resistors with a very good temperature coefficient (25 PPM.). As these were military types they are much bigger than other resistors that are rated for ¼ watt since they are expected to be used at higher temperatures. Figure 5 shows these.

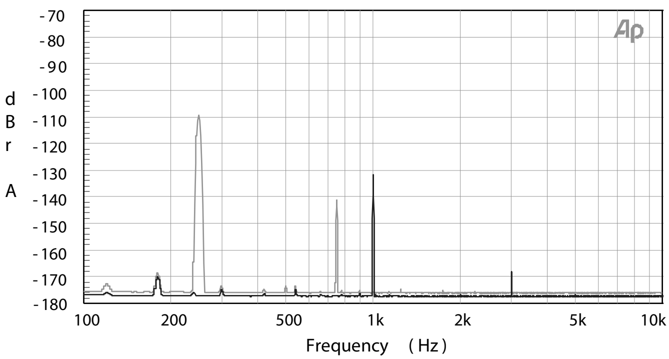

Figure 4 Vishay S102 1K 1/4W resistors

The interesting feature of a RN65 like the S102 is not just the low distortion, but the second harmonic distortion. Second order distortion is often perceived as being more musical

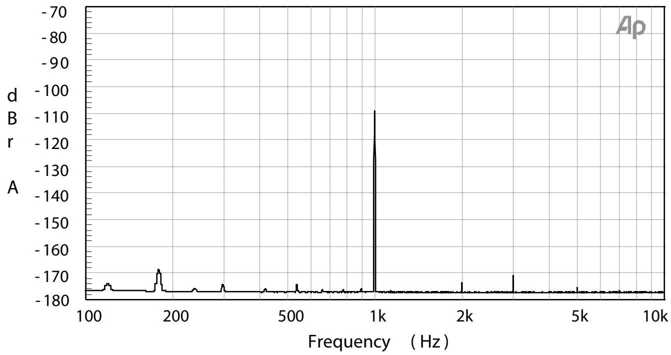

Figure 5 Dale RN65E S102 25PPM military. Note low distortion but also 2nd harmonic. 15.8V/1kHz.

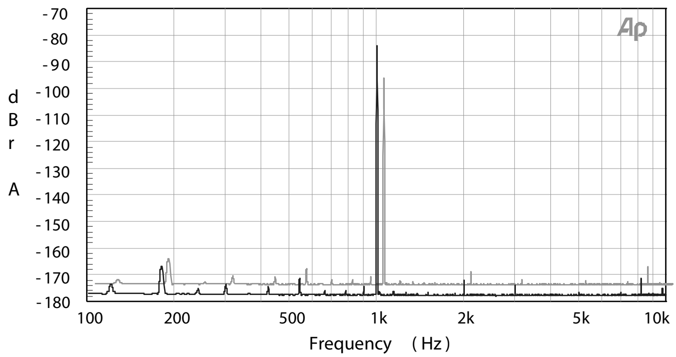

Figure 6 RN65C, top (10dB offset); RN65D, bottom

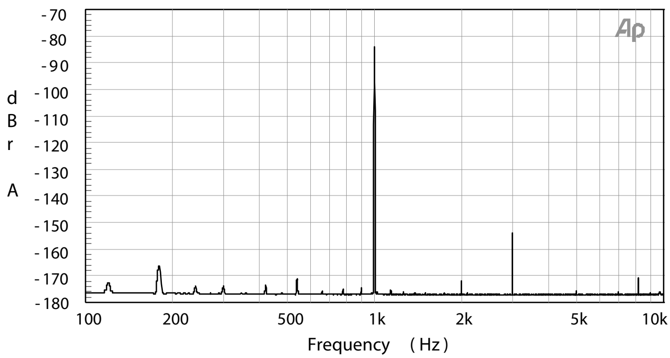

Figure 7 Dale commercial metal film mini case

than odd orders and is not particularly unpleasant even at high levels. Another feature to note is the low noise floor. This is not just shown by the base line but also by the lack of base spreading at 1 kHz. As these seemed to be the best resistors I had they became the reference for the test system.

I now fixed my test unit with 8 of the Dale RN65E resistors as a reference and began to try other resistors. Dale RN65C (50PPM) and RN65D (100PPM) were tried with the final test circuit. I used 15.81 volts as my 0db reference.

Both showed excellent performance (figure 6). I then tried the same type of resistor but in the commercial range, meaning they were rated for ¼ watt at lower temperature and were much smaller in size. Figure 7 shows the results, less heat dissipation capability caused the expected increase in third harmonic distortion. The second harmonic seemed to be a characteristic of the material used. So there's a valuable lesson here: these resistors are an excellent choice as long as the power levels are kept quite low, or when using higher values of resistance.

I then tried a Holco H4 ½ watt resistor another popular audio choice. This is shown in figure 8. A nice clean example of an audio resistor, although with the ½ watt rating one would expect the third harmonic to be 6 db down from an equal quality ¼ watt unit.

Another commonly used part is the ¼ watt 1% metal film resistor from Xicon. This is shown in figure 9. These showed no second harmonic but a bit more third than the "audio" resistors. Other metal film types showed some second harmonic distortion so the Xicon was a bit better than most of the low cost metal film types on the second but does have more third harmonic than some.

Many audio folks like to use wire-wound resistors so a sample of the Mills MRB-5-Ni was also tested. This is shown in figure 10

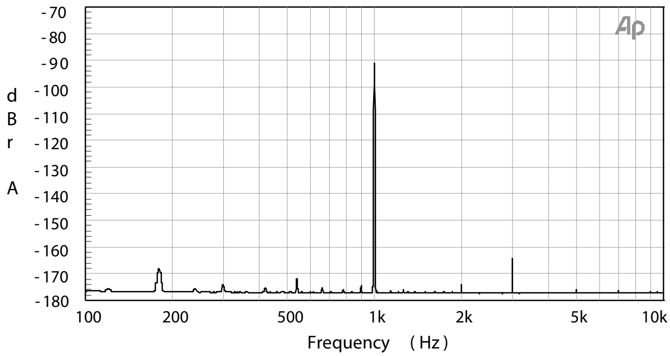

Figure 8 Holco H4 ½ Watt

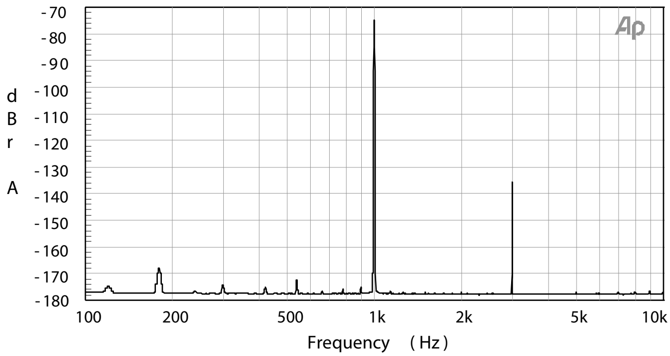

Figure 9 Xicon 1% ¼ watt metal film

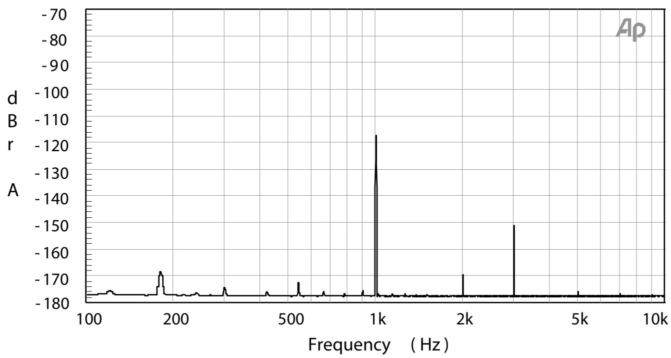

Figure 10 Mills MRB-5Ni 5 watt wirewound

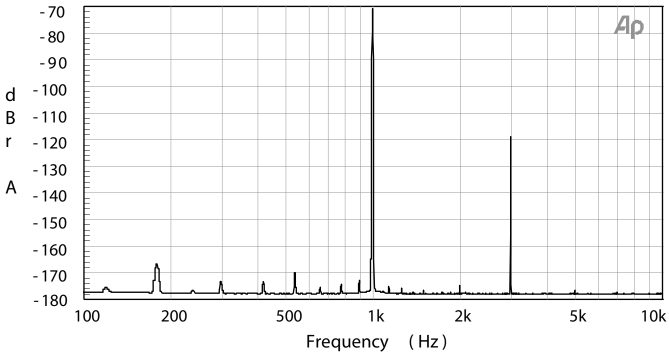

Figure 11 KOA carbon film resistor 1/4W 5%

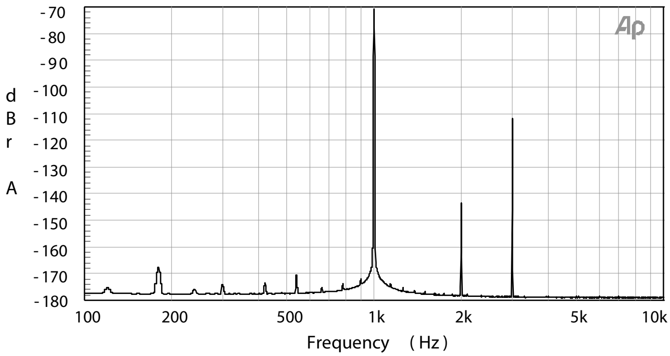

Figure 12 KOA miniature carbon film resistor

Although the distortion is about the same as the ¼ watt inexpensive metal film resistors, this is a 5 watt unit and should have a 26 db advantage! Although I didn't have a low distortion signal source with enough voltage (35.36 V) to drive these resistors to a higher level, I would expect the distortion to increase the same as all of the others.

The most common resistor used today is the carbon film type. A typical sample is shown in figure 11. Interesting to note is that to null the 5% resistors I had to disconnect the 25 ohm balance trim and use the entire 100 ohm range of the ten turn pot. This results in less of a 1 KHz null, but it really doesn't show up as increased second harmonic. The third harmonic is now approaching -120 db or a bit less than 20 bits of resolution could be had with these resistors. Note also the spreading of the 1 kHz spike's base width.

KOA also makes a ¼ watt rated carbon film resistor in the size that used to be 1/8 of a watt. This is shown in figure 12. No big surprises here. This resistor heats up more, has more distortion and as the base spreading shows, is actually generating some noise from the primary exciting voltage. This resistor would not just add some border line harshness but also would begin to mask detail! This is most likely a part not to be used for any critical path in an audio circuit.

Of course there is also the classic carbon composition resistor. I tried several samples and a typical result is shown in Figure 13. As you can see the distortion and noise levels are much higher than any other resistor. This was also a difficult resistor to trim as the temperature coefficient was high enough for room temperature changes over the test period to cause a drift in the null.

When the operating level is reduced the third order drops as does the second order. With a bit of finesse this could actually be used to increase the even order distortion in a signal. So some may actually like the decrease in detail and false harmonics!

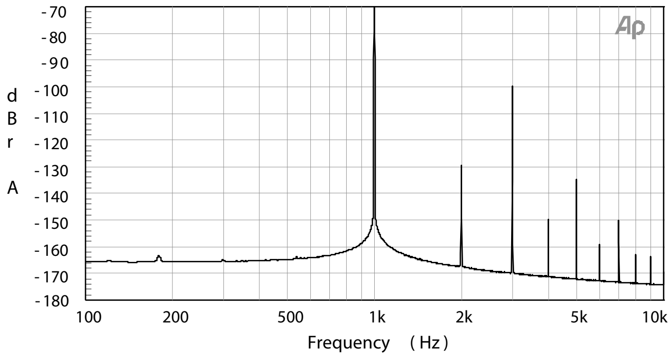

Figure 13 OHMITE carbon composition ¼ W 5%

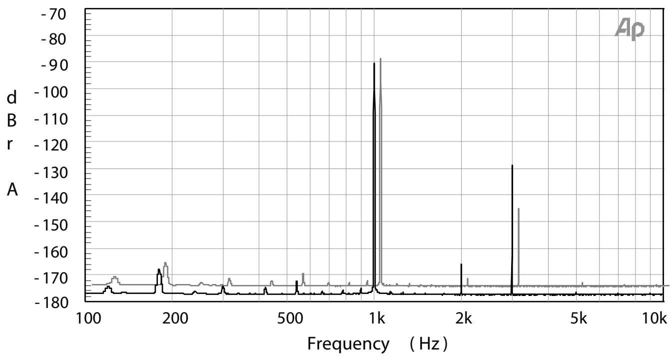

Figure 14 Tantalum chip; 7.5V (top, offset) and 15.8V

There are also those who like Tantalum film resistors. I found an IRC model PFC-W0805LF-03-1001-B Chip resistor. It is smaller in size than most other ¼ watt chips and the results are shown in figure 14.

As a ¼ watt rated resistor the performance is not very notable, but if used as a 1/8 watt it is on par with many of the best.

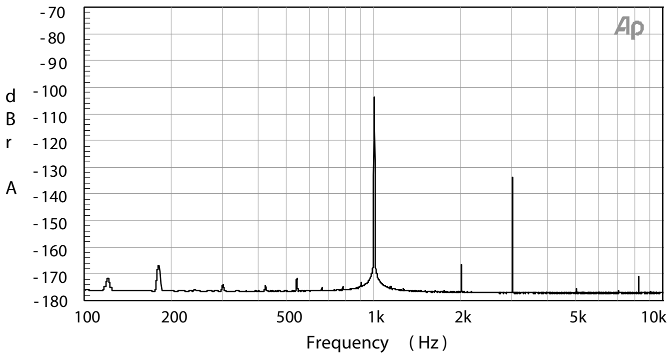

Figure 15 Panasonic miniature metal film

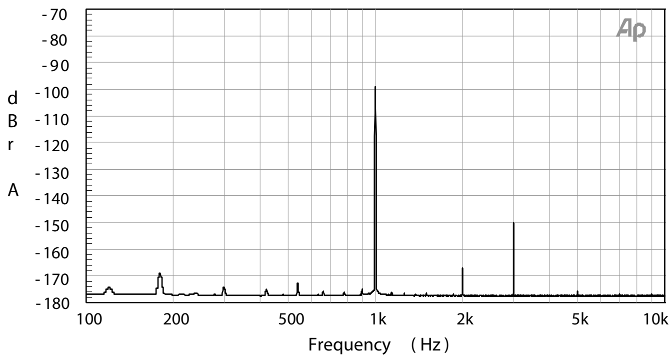

Figure 16 Caddock TF-020R metal film

Another interesting resistor was a miniature commercial metal film resistor from Panasonic shown in Figure 15.

Again not quite as good as many but at lower power levels it may be an inexpensive choice. I would not try this unit at higher resistance values as the noise level is already beginning to show.

Not shown is the Princeton Resistor Products PRP 9372 1/2W 1 Metal Film. It tested almost the same as the Holco H4 (figure 8), just a bit more third harmonic. The performance is quite good for such a low cost resistor.

Another popular audio resistor choice is the Caddock TF-202R 1% 15PPM as shown Figure 16. With second harmonic just a bit above -170 and the third at -150 this may be an excellent choice at low power levels where these distortions would drop. So these may be a good choice for higher resistor values.

Audio designer John Curl prefers the Roederstein Resista old stock resistors. These are a low cost 1/2 watt metal film resistor. The results are shown in Figure 17. Yes these turned out to be among the best resistors tested and almost the least expensive! Note that this is a ½ watt unit. As a result the third harmonic distortion is lower than if it were a ¼ watt type. Of course they are only available as unused old stock!

Today much audio gear is going to surface mounted components. Figure 18 shows the results on a Vishay 1206 size Thin Film chip resistor. This should be compared to Figure 7 where a similar leaded resistor is shown. If this chip resistor was de-rated to 1/8 watt it would be quite comparable.

Figure 19 shows a Vishay 1206 Thick Film resistor. This resistor chip has more distortion than the more expensive thin film version. This curve was similar to most of the thick film chip resistors tested, so even de-rating these to ½ power they are still quite lacking.

Wrap-up This of course is only one way to look at resistors. Also, be aware that actual resistor distortion in a circuit will most probably be higher then the reference numbers shown with this self-comparison type of testcircuit. But with some thought you can influence the performance of your audio designs by choosing parts for the distortion and power handling characteristics that are in line with your design goals. And lest you think I thought of all this just by myself, I wish to thank Scott Wurcer of Analog Devices, Inc and Demian Martin of System Design Services, for contributions to this project.

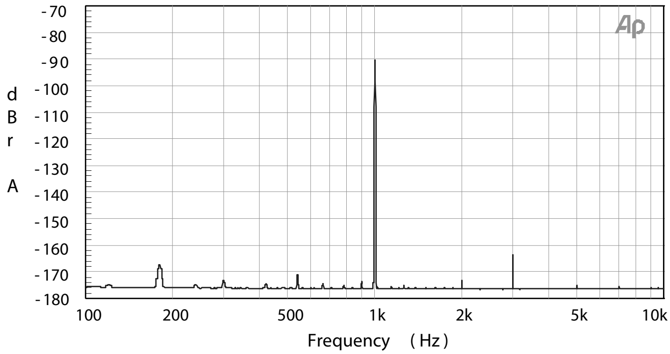

Figure 17 Resista ½ W 5% resistor 'old style'

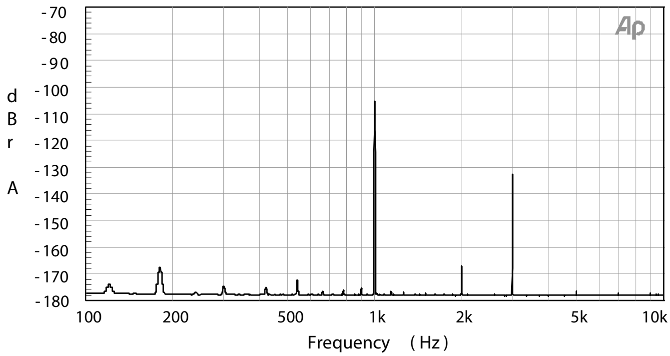

Figure 18 Vishay 1206 thin film ¼ W 25 ppm

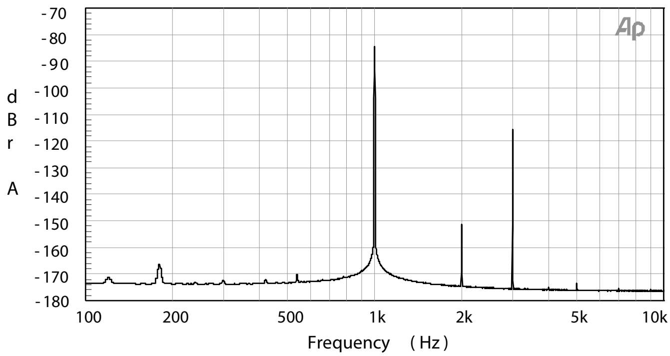

Figure 19 Vishay 1206 thick film resistor