Revision History
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Revised 02 November 2008 - added data for Walters OEP8000 transformer
Revised 23 April 2009 - added data for three Stancor transformers and Jensen DIN-2LI transformer module
Revised 25/26 July 2009 - added data for BG Incorporated KS transformer

Introduction

I've written about linear transformer models at Audio Transformer Data and Modeling, and at Softrock Lite 6.2 and about ferrite core based RF transformers at Ferrite Transformers. And, I've explored in some detail the problems stemming from Elecraft's choice of a Tamura TTC-108 audio transformer to provide LINE OUT isolation in its K3 transceiver at Elecraft K3 Receive Audio. My Elecraft K3 Receive Audio page has a great deal of additional non-linear performance measurements for the Tamura TTC-108 transformer and should be read as a supplement to this page for a full understanding of non-linear transformer behavior.

My Elecraft K3 studies, unlike the other pages, looked at both linear and non-linear problems with the TTC-108. Linear transformer concerns are most commonly related to frequency response and, less commonly, phase shift. Non-linear behavior results in waveform distortion, evidenced by harmonic generation and intermodulation distortion.

This page focuses on non-linear transformer behavior. Although started as an extension to my Elecraft K3 audio explorations, I've expanded the scope of these studies to other transformers and hence decided the topic justifies its own web page.

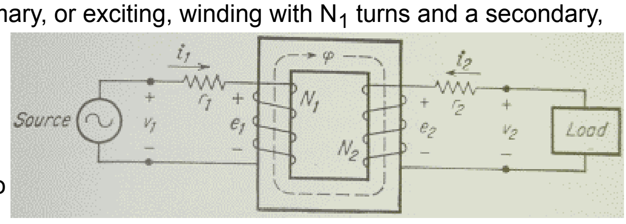
Albert Einstein one said--although in more formal language--ï¿½everything should be made as simple as possible, but no simpler.ï¿½ To understand why transformers produce non-linear distortion requires a detailed look at magnetic material behavior. I'll make the explanations and mathematics as simple as possible, erring on the side of over-simplification.

I'll also add that I've written many magazine articles, an 800 page book on computer programming as well as this web page, not to mention thousands of documents I've worked on professionally whilst practicing law for 30 years. This web page turns out to be among the most difficult I've written, and fails to meet my standards of clarity. Generally this means I don't understand the subject as well as I should, and I apologize in advance. When growing up, I recall an expression used in my family, ï¿½he doesn't understand all he knows about it.ï¿½ This expression applies hereï¿½I have learned quite a bit about transformers in my measurements and research, but I fear that I don't quite understand all that I've learned.

If you are interested in only the measured results, skip the next sections and jump right to the measured data.

Transformer Fundamentals

Before considering non-linear effects, we'll quickly review how a transformer works. Consider the case of a transformer with a primary, or exciting, winding with N_1 turns and a secondary, or second, winding of N_2 turns as illustrated to the right.



Assume, for the moment, that the secondary winding has no connection to the load and hence no current flows through it. If an AC voltage source is applied across the exciting winding, an AC current, i_1, flows through the winding, producing an alternating magnetic flux φ in the core, as provided in Ampere's law. The flux φ is proportional to i_1 and the number of turns on the exciting winding.

Faraday's law says that a time changing magnetic flux induces an alternating voltage in the turns of any coil threaded by the flux, in this case both the exciting winding and the second winding. Mathematically, each turn of the coil has a voltage *e* induced across it of $e = d\varphi /dt$, where $d\varphi /dt$ is the derivative of the flux, *i.e.*, the instantaneous rate of change of the flux with time. (Faraday's law has a minus sign indicating the polarity with respect to the flux change. Our discussion will ignore the sign.)

Assuming an ideal transformer, the same flux threads both the exciting and second windings.

The exciting winding's (winding 1) induced voltage is thus $e_1 = N_1 d\varphi /dt$

The second winding (winding 2) has a similar voltage induced across its turns $e_2 = N_2 d\varphi /dt$

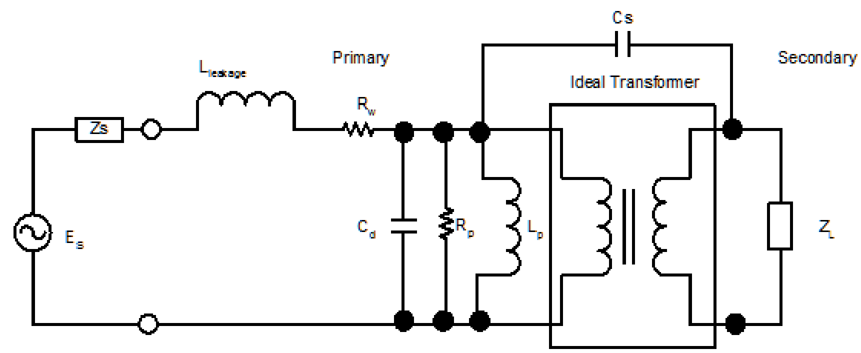
N_1 and N_2 are the number of turns on the exciting and second windings, respectively.

Since we've assumed an ideal transformer with the same flux linking both windings, $d\varphi /dt$ is the same for both windings and the standard transformer relationship of turns and voltages can be found:

$e_1/e_2 = N_1/N_2$

For many applications, this simple relationship is all we need to knowï¿½the voltage ratio is proportional to the turns ratio.

We can, however, obtain a better understanding of real world transformers by adding the more important parasitic elements to this theoretically perfect transformer. The schematic below identifies the principle parasitic elements of a real transformer. Remember, this is still a linear modelï¿½these parasitic elements only alter the frequency and phase response and do not model non-linear responses.



- Lleakage is the leakage inductance
- Rs is the series resistance of the winding
- Cd is the distributed capacitance
- Rc is the core loss
- Lp is the magnetizing inductance

These parameters are usually "reflected back" to the primary, *e.g.*., we assume the series resistance is all in the primary, by treating it as the sum of the true primary resistance plus the secondary resistance scale by the square of transformer's turns ratio $(N_1/N_2)^2$. Likewise for the secondary leakage inductance.

In the same fashion, Zload is transformed back by multiplying by $(N_1/N_2)^2$. For example, if the load is a 1000 ohm resistor, and if the secondary winding N_2 has four times as many turns as the primary, N_1, then the primary side ï¿½seesï¿½ a resistance of 1000 x $(1/4)^2$, or 62.5 ohms. Although our example uses a pure resistance, the N^2 transformation ratio applies to the general Z = R+jX case as well.

My Audio Transformer Data and Modeling page compares the predicted response against measured response of an audio transformer using this model. In general, if the parameters are accurately determined (and if they don't change too much over the frequency and amplitude range measured) very good agreement between model and measured data is possible.

Magnetic Flux Inside the Transformer

In order to understand why transformers cause non-linear distortion, we'll look in more detail at the relationship between applied exciting current and magnetic flux. The following discussion is from Snelling, ï¿½Soft Ferrites Properties and Applications.ï¿½

The magnetic field strength, H, inside a very long uniform solenoid having N_1 turns per axial length l and carrying I amperes is given by:

$H=N_1 I/l$ A m^{-1}

Its direction is parallel to the axis of the solenoid and is uniform across the cross section.

The associated flux density, B, is given by

$B = \mu_0 H$ tesla (T)

where μ_0 is the magnetic constant or the permeability of free space. It has the numerical value $4\pi \times 10^{-7}$ and has the dimensions henries/meter or $[LMT^{-2}I^{-2}]$. Thus in the SI units, flux density is dimensionally different from field strength.

If the solenoid is now filled with a magnetic material, the applied magnetic field will act upon the magnetic moments of the ions composing the material ... the ions, by virtue of the spinning electrons, behave as microscopic current loops each having a magnetic moment. ... Under the influence of an applied field, the ion moments are reorientated ... so that the ionic moments augment the applied field. This increase in magnetic field is called the magnetization, M, and it is expressed in A m-1 ... The internal magnetic field becomes

Hi = N1I/l + M A m-1

and the flux density becomes

$B = \mu_0 H_i = \mu_0(H+M)$ T

or

$B = \mu_0 H + J$ T

where J is the magnetic polarization in teslas; it is sometimes referred to as intrinsic flux density

$J = \mu_0 M$ T

...

$B/H = \mu_0 \mu$

where μ is relative permeability.

As more usually stated, $B = \mu_0 \mu H$

If the B is uniform across the cross section of the core, the magnetic flux, φ, is:

$\varphi = BA$ webers (Wb)

A is the cross sectional area of the core in square meters.

From Faraday's law, the induced voltage, e_2, into a coil of N_2 turns from a varying flux is

$e_2 = -N_2 A\, dB/dt$ volts (V)

The negative sign is because the induced voltage is such that it (assuming a closed circuit) creates a current opposing the changed flux.

Stated in terms of the driving magnetic field strength, H, the induced voltage (and dropping the negative sign for convenience) is

$e_2 = N_2 A \mu_0 \mu\, dH/dt$

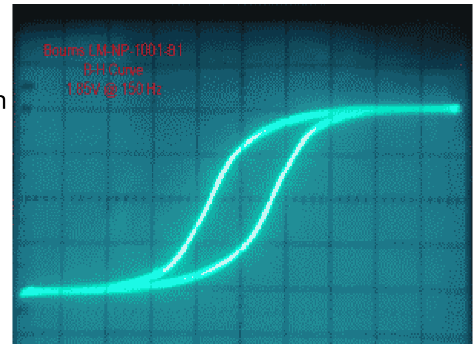
Inductance, L, is related to flux linkage per unit current

$L = N\Phi/I$ henries (H)

where I is the peak AC current in amperes.

B-H Curve

From these relationships, therefore, the transformer's output voltage is a function of the rate of change of the input current multiplied by the permeability.



From our discussion, it might seem that μ is a constant and thus the relationship between B and H is linear. This is far from the case with practical magnetic core materials. The relationship between B and H is commonly shown through a ï¿½B-Hï¿½ plot, such as the one illustrated at the right. (This B-H curve is data I've measured of a Bourns LM-NP-1001-B1 audio transformer further analyzed below.)

The horizontal axis is proportional to the winding current and, for our purposes can be considered to be H, the magnetic field strength. the current I. The vertical axis is the integral of the applied voltage, and is thus proportional to the magnetic flux, B.

Looking at the B-H relationship shows that for any H (or for any current i), there are two possible B values, depending upon H's history--was H increasing or decreasing from its peak? It also reveals that significant parts of the B-H curve are non-linear.

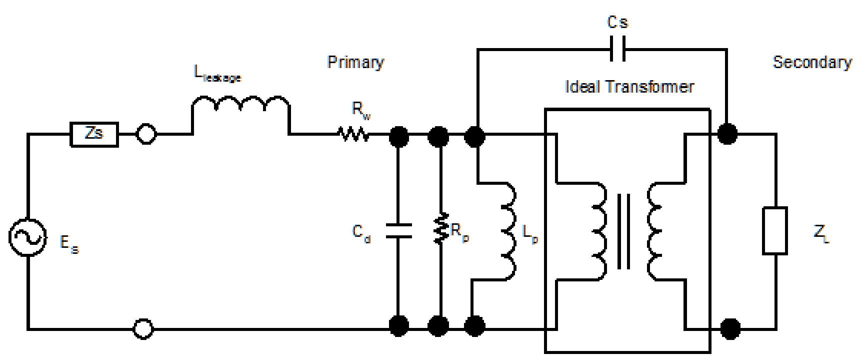
The area within the B-H curve represents hysteresis energy loss, which is a component of the total "core loss" along with eddy currents and other losses. Hysteresis can be defined as ï¿½The phenomenon by which an effect in a component depends not only on the present stimulus, but also on the previous state of the component.ï¿½ In other words, which B state corresponds to a particular H depends on how the H value is arrived at ,*i.e.*, its history.

If B-H is so non-linear, how can a transformer deliver even relatively low distortion output? The answer is that a feedback mechanism helps make the output waveform match the input waveform.

The transformer's input voltage causes a current to flow through the primary windings and as discussed earlier generates a magnetic flux B flowing through the core. B threads both the primary and secondary windings more or less equally, and hence dB/dt induces an opposing voltage in the primary winding, even where there is no current flowing in the secondary because it's open circuited. This opposing primary voltage, in a well designed transformer, almost equals the applied voltage when the secondary is open circuited, with the difference causing the ï¿½magnetization currentï¿½ to flow.

When a load is placed on the secondary, current flows through it and a magnetic flux is generated opposing the flux generated by the primary current. The secondary's opposing flux causes a reduction in dB/dt at the primary and the corresponding induced opposing voltage, thus causing increased primary current flow, so that the net flux through the core is unchanged from the no-load condition. (This should be understood to be working instantaneously.) If the primary's source can supply the necessary current, the output waveform reflects the input waveform, since the same dB/dt is seen by both the primary and secondary windings, regardless of how linearly or non-linearly B and H are related.

Let's return for a moment to our linear transformer model. This demonstrates several reasons why the primary winding cannot supply exactly the correct current to cause the transformer's inherent feedback mechanism to work perfectly.



One major problem is the series impedance, comprising the winding resistance Rw, the leakage inductance Lleakage and the source driving impedance Zs. As the load on the secondary requires greater or lesser current in the primary at any given instant, the ability of the driving voltage source Es to deliver the correct current current to the primary winding is constrained by this series impedance.

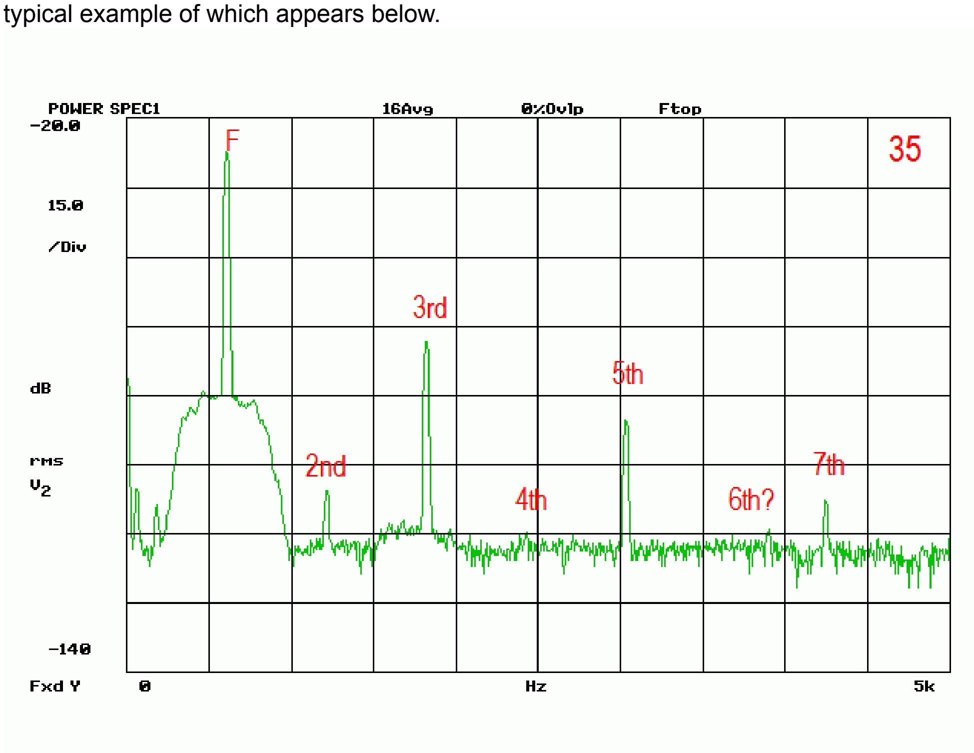
Even if we make Es a very low impedance source, such as a feedback amplifier, the transformer's internal impedance limits the ability of the primary winding to provide the required current and corresponding magnetic flux to exactly match the value required for distortionless operation. Since Faraday's law applies, the secondary waveform distorts to match the available dB/dt.

If the driving impedance Zs is large compared with the transformer's internal impedance, distortion increases for this reason; if Zs is small compared with the transformer's impedance, distortion can be reduced. Of course, the transformer's internal impedance places a lower bound on the distortion improvement resulting from a zero ohm driving source. (A feedback amplifier, such as an op-amp buffer can have an output impedance of a fraction of an ohm and approaches a perfect voltage source within its current limits.)

One additional point before proceeding to the measured data. For a given sinusoidal voltage applied across the transformer primary, the currentï¿½and H, of courseï¿½is inversely proportional to the frequency. This is because dB/dt increases directly with frequency. For a sinusoidal of the form B sin(ωt), dB/dt is B ω cos(ωt). Hence for a given induced voltage, *i.e.,* constant dB/dt, B (and, of course H) must decrease as ω increases. (The symbol ω is the frequency in radians/second, or ω = 2πf where f is the frequency in Hz.) Therefore, as the applied frequency increases, H and B decrease. This means that a transformer's core material related non-linearities are most pronounced at low frequencies as increased H drives B into non-linear portions of the B-H curve.

Why Does Odd-Order Distortion Predominate in a Transformer?

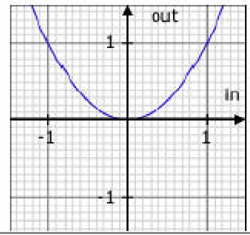
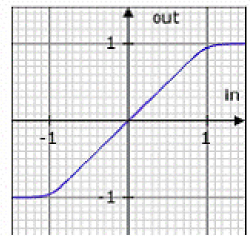
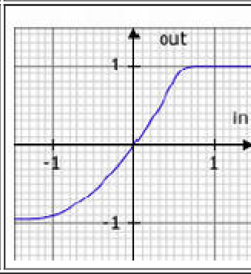
Data at my page http://www.cliftonlaboratories.com/elecraft_k3_receive_audio.htm presents spectrum analyzer plots of the K3's LINE OUT audio (which uses a TTC-108 transformer), a typical example of which appears below.



The second harmonic in this example is down approximately 70 dB from the 600 Hz fundamental, whilst the third harmonic is down less than 40 dB. A similar effect is visible with the fourth harmonicï¿½not visible above the noiseï¿½and fifth harmonic, as well as the sixth and seventh harmonics. Odd order harmonics are 30 dB or so stronger than even order harmonics.

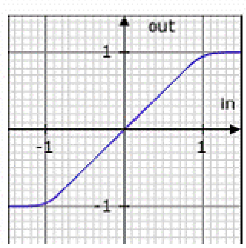
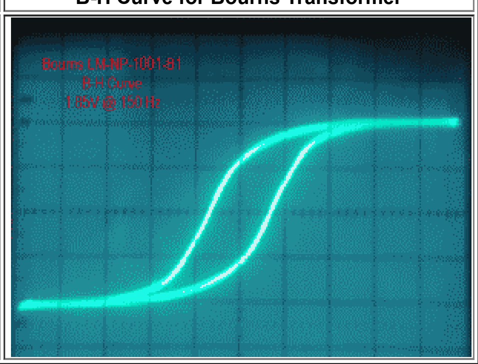
The reason for this behavior may be summarized in one wordï¿½symmetry. Mathematically speaking, the B-H curve can be regarded as a transfer function. We may consider the transformer's input waveform as consisting of a series of discrete voltage points x. (x is a function of time, of course). The output voltage x' is a function of the B-H curve, so that x' = f(x), where the function f describes how a signal point on the transformer primary is modified into a signal point on the secondary. In engineering, f(x) is called the ï¿½transfer function,ï¿½ as describes how an input signal is transferred to the output.

Transfer functions have three possible symmetries:

Symmetry Type	Sample Plot	Distortion Type
Even symmetryï¿½where f(x) = f(-x)		Only even order distortion is created
Odd symmetryï¿½where -f(x) = f(-x)		Only odd order distortion is created.
No symmetryï¿½where the function has neither even nor odd symmetry		Both even and odd order distortion is created.

These plots are from http://www.rs-met.com/documents/tutorials/Waveshaping.pdf which contains a more mathematically detailed analysis of symmetry and distortion.

Comparing the odd symmetry example with one of my measured B-H curves should convince you that the B-H curve possesses odd symmetry and thus transformers will demonstrate odd order harmonic generation. Of course, the B-H curve is not perfectly odd symmetrical, but it's close enough that the even order harmonics are down 30 to 40 db from the odd order harmonics.

Odd Symmetry Example	B-H Curve for Bourns Transformer
	

Non-Linear Transformer Modeling in SPICE

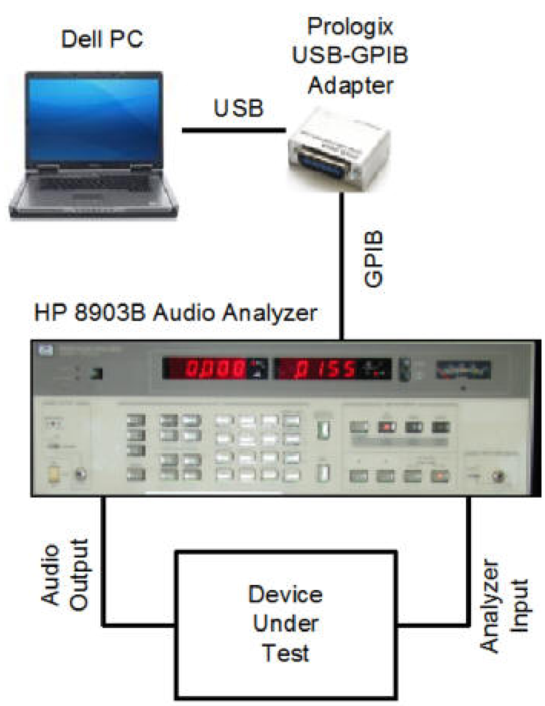
This is as good a place as any to mention that SPICE circuit modeling tools include non-linear transformer modeling as well as linear transformer models. LTspice, the program I use, has two non-linear inductor (and transformer) models:

> There are two forms of non-linear inductors available in LTspice. One is a behavioral inductance specified with an expression for the flux. The inductor's current is referred to by the keyword "x" in the expression. Below is an example in a netlist:
>
> ```
> *
> L1 N001 0 Flux=1m*tanh(5*x)
> I1 0 N001 PWL(0 0 1 1)
> .tran 1
> .end
> ```
>
> There other non-linear inductor available in LTspice is a hysteretic core model based on a model first proposed in by John Chan et la. in IEEE Transactions On Computer-Aided Design, Vol. 10. No. 4, April 1991. This model defines the hysteresis loop with only three parameters:
>
> | | | |
> |---|---|---|
> | Hc | Coercive force | Amp-turns/meter |
> | Br | Remnant flux density | Tesla |
> | Bs | Saturation flux density | Tesla |
>
> In addition to these magnetic properties, the mechanical dimensions of the core are required:
>
> | | | |
> |---|---|---|
> | Lm | Magnetic Length(excl. Gap) | meter |
> | Lg | Length of gap | meter |
> | A | Cross sectional area | meter**2 |
> | N | Number of turns | - |

This information is not simply obtained when reverse engineering a transformer, at least not without disassembling a couple of samples, so the practicality of non-linear modeling of an existing off-the-shelf transformer remains problematic for the casual experimenter.

Measurement Setupï¿½Distortion Data

The distortion data (and frequency response data) is taken with an HP 8903B audio analyzer, controlled with software I've written.

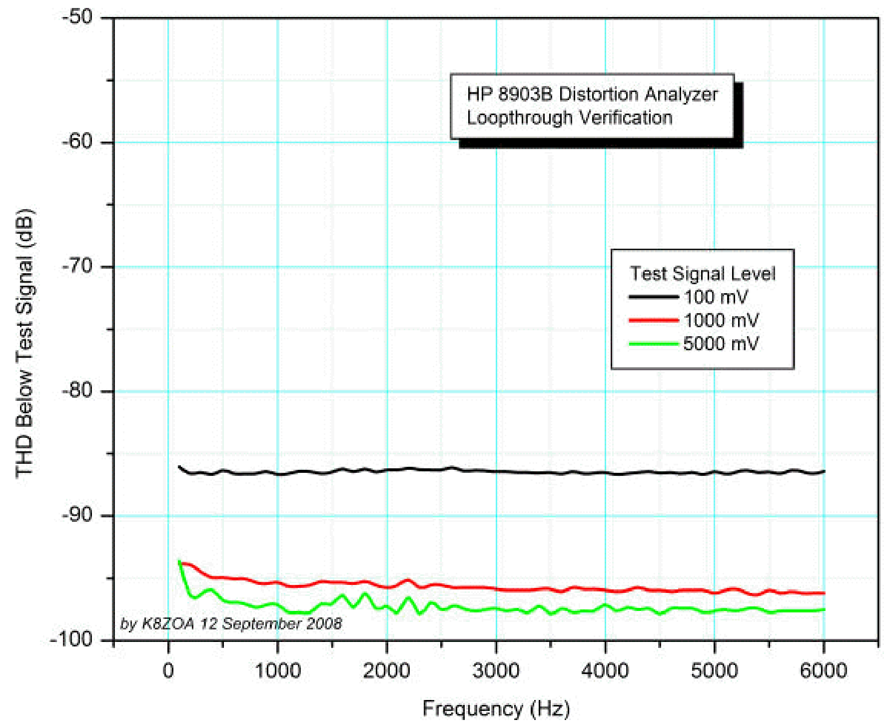


The 8903B has a low-distortion signal generator with a range of 20 Hz ï¿½ 100 KHz, with output impedance of 50 or 600 ohms selectable by GPIB command. Maximum open circuit voltage is 6V RMS. The 8903B's generator is specified as having harmonics and noise < 80 dB below the carrier over the frequency range 20 Hz ï¿½ 20 KHz.

The 8903B's analyzer section works in the same fashion as a classic analog distortion meter. The applied test signal frequency is notched out and the residue, consisting of test signal harmonics, hum and noise is measured. The ratio between the test signal and the residue is the ï¿½total harmonic distortionï¿½ or THD ratio. The analyzer section has switchable low pass filters of 30 KHz and 80 KHz, along with a ï¿½full bandwidthï¿½ mode of 750 KHz. Reducing the analyzer bandwidth is appropriate for the tests I've run as noise and harmonics above 30 KHz are not meaningful. (Distortion data over the range 20 Hz - 20 KHz uses the 80 KHz low pass filter.)

In interpreting the test data, it's necessary to understand how the test signal level influences the minimum measurable THD. The analyzer cannot distinguish broadband noise from harmonics. Likewise, if the applied test signal is not notched down below the instrument's noise floor, its contribution will also appear as part of the reported THD. Accordingly, the dynamic range available is a function of the signal level at the 8903B's analyzer section input.

The plot below shows a loopback test of the 8903B, where the instrument's audio generator output is connected directly to its analyzer input.



At 100 mV, the instrument is limited by the 8903B's analyzer section noise floor. (All data taken with 30 KHz low pass filter enabled.) The noise floor is about 86 dB below 100 mV, or 5.01 μV summed over a 30 KHz bandwidth. The 8903B's noise floor specification is less than 15 μV with 80 KHz bandwidth, so after adjusting for the narrower bandwidth, the measured noise floor is well below the maximum specification.

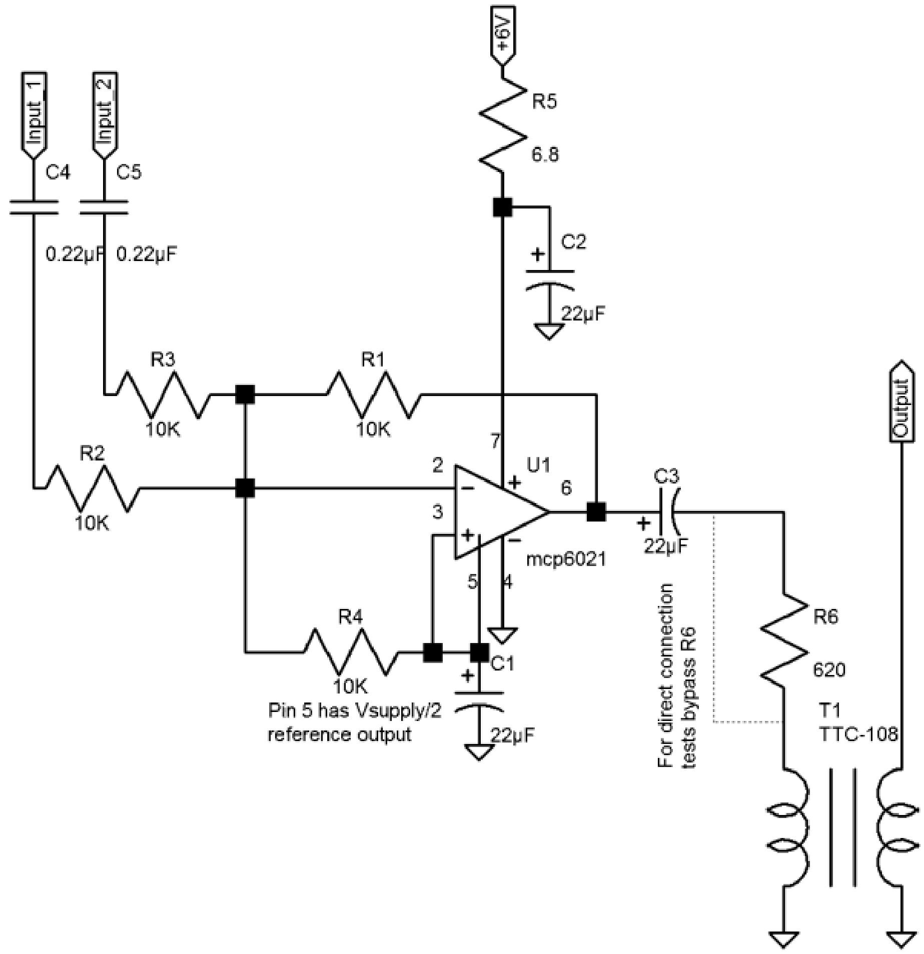
The instrument's noise floor does not change with input signal level, but as the test signal level increases, the reported ratio between the test signal and residue (the THD ratio) naturally increases. With 1000 mV test signal, the reported THD is about -95 dB at 1 KHz, corresponding to 17.8 μV. We thus see about 13 μV contribution of source harmonics and possibly fundamental leakage through the notch filter, plus 5.1 μV noise. At 5000 mV, the reported THD is -97 dB, or 70.6 μV, comprising a mix of source harmonics and fundamental leakage due to finite notch depth.

All these figures are well below the 8903B's maximum specifications.

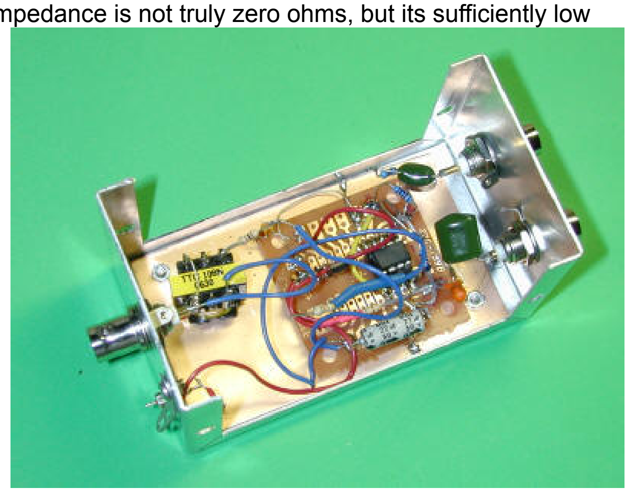
The point to remember is that some data will be limited by the 8903B's noise floor, particularly where the input signal is relatively low.

"Zero Impedance" Driver Circuit

In addition to connecting the transformer directly to the 8903B's signal source, I've taken some data with a zero ohm driving source, as discussed at Elecraft K3 Receive Audio The schematic below shows the zero ohm driving source.

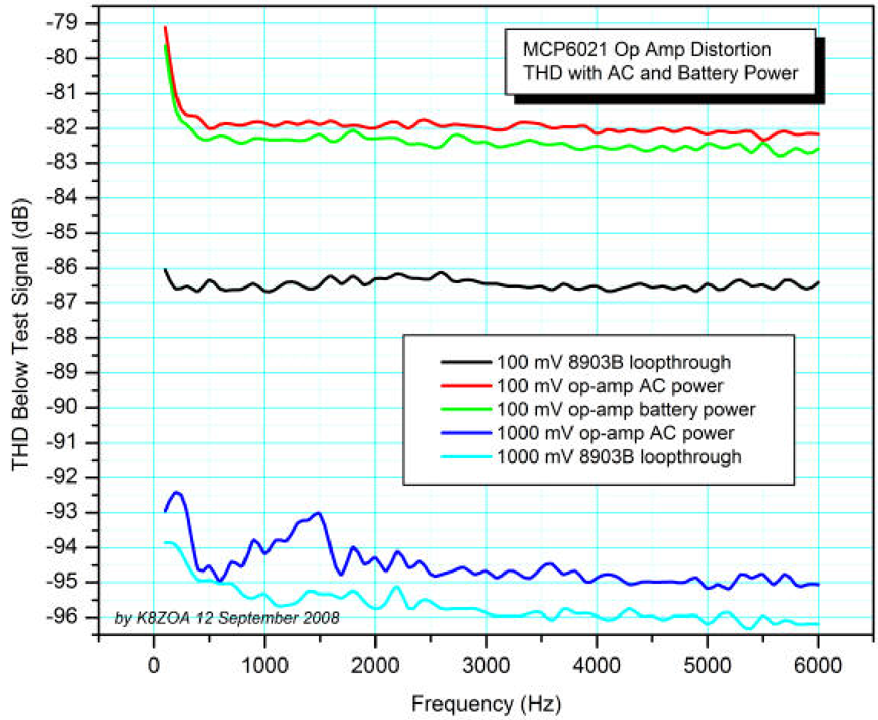


Of course, the MCP-6021's output impedance is not truly zero ohms, but its sufficiently low that we can consider it to be zero ohms without introducing significant error.



To verify that the op-amp was not adding distortion or noise, I ran a series of tests with the MCP 6021's output directly connected to the 8903B audio analyzer. The op-amp driver is normally powered from an HP E3610A variable voltage power supply, so to see if that introduced additional hum and noise, I also ran tests with the op-amp circuit powered by a 9 volt battery. (The circuit has an on-board voltage regulator not shown in the schematic.)

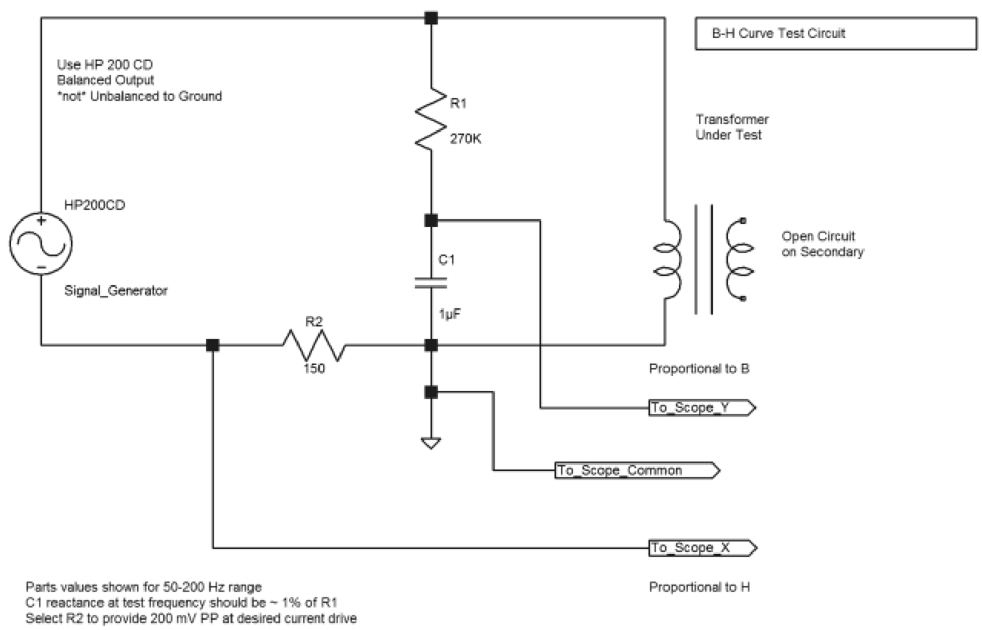
The data shows that there's very little hum and noise added by AC power, perhaps 1 to 1.5 dB, so for convenience the transformer tests were run with the E3610A power supply.



The plot also shows the 8903B's loopthrough THD. We see that the op-amp circuit adds about 4 to 4.5 dB THD to the test circuit at the 100 mV level. At 1000 mV, however, there's about 1 dB difference between the op-amp and the instrument loopthrough data. This suggests that the op-amp circuit adds about 4 to 5 dB broadband noise, but very little harmonic distortion. (An alternative explanation is that at low signal levels, the MC) 6021 exhibits crossover distortion.)

Measurement Setupï¿½B-H Curves

The B-H curves presented were taken with the simple circuit shown below, originally published in Electronic Design. http://electronicdesign.com/Articles/Index.cfm?AD=1&ArticleID=6155



R2 provides a sample of the drive current, and thus the voltage at ï¿½To Scope Xï¿½ is proportional to H. Obtaining a B sample is slightly more difficult. The voltage across the transformer primary is proportional to dB/dt, so by integration, we obtain a voltage proportional to B. R1 and C1 are a simple RC integrator.

The B and H values are not calibrated, but rather provide data proportional to the real B and H. For our purposes, that's adequate.

Measurement Setup - Pulse Ringing

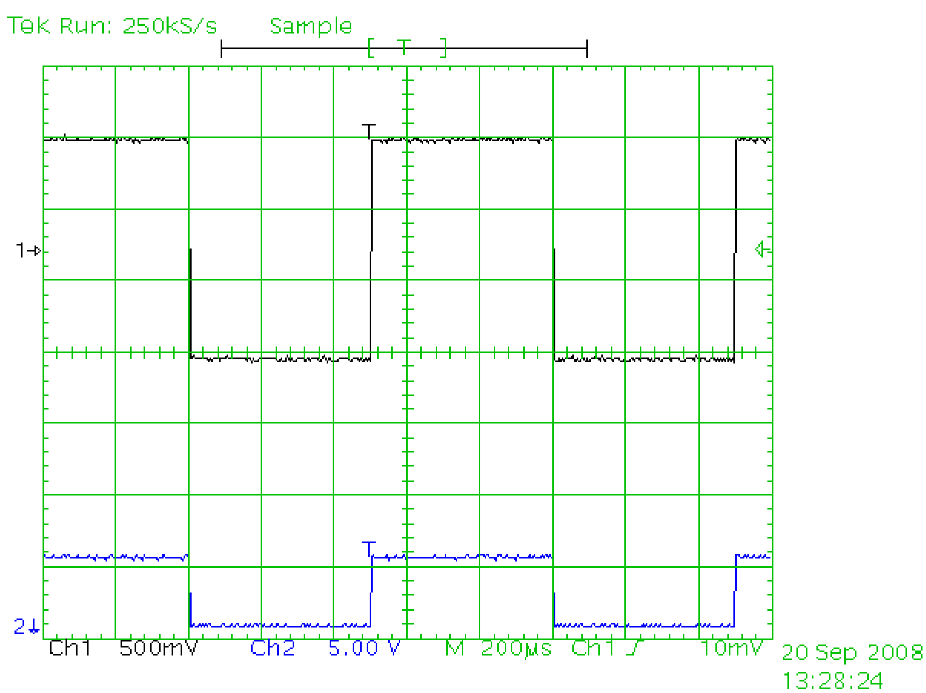
I've also looked at the response of the these transformers to a 1 KHz bipolar square wave. This may be argued as an unrealistic test, since audio does not consist of square waves. Moreover, a bandwidth limited communications receiver is incapable of generating fast rise/fall waveforms. I've included the data because (a) I collected it and (b) there seems to be a belief in certain audio circles that ringing generated by a square wave is an important evaluation criterion.

The oscilloscope image below shows the test signal (trace 1). Trace 2 is a synchronization pulse from the Telulex SG-100 function generator used in this test.

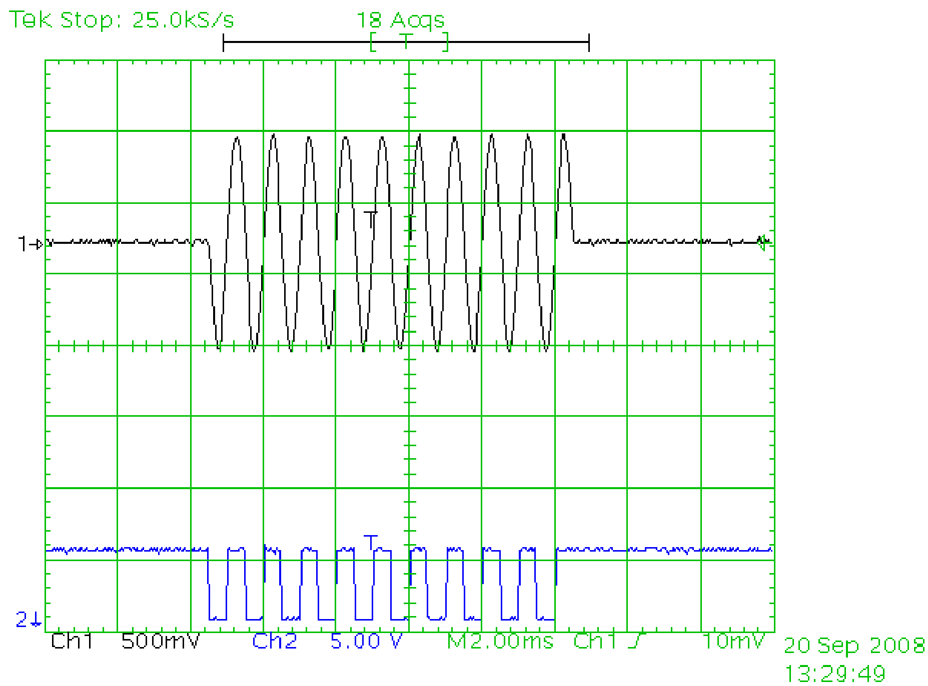
Four configurations were studied for each transformer tested with square waves:

- 50 Ohm drive resistance; high Z (oscilloscope input) termination
- 50 Ohm drive resistance; 620R termination
- 610 Ohm drive resistance; high Z (oscilloscope input) termination
- 610 Ohm drive resistance; 620R termination.

The 610 drive resistance was obtained by a series 560 ohm resistor in the SG-100's output. The 620 ohm termination is a 5% carbon film resistor of that value installed in the body of a male BNC connector, mounted at the oscilloscope input with a BNC "T" connector. The oscilloscope used is a Tektronix TDS-430.



I also looked a the transformers with what I regard as a more realistic case, a burst of 10 cycles of 1000 Hz sine wave, as illustrated in the oscilloscope image below. Because the sine burst ends at a zero crossing, there is no ringing observed in any of the transformers tested.



Transformers Studied

I looked at ten transformers, four of which are shown in the photograph at the right.

- Tamura TTC-108
- Triad SP-70
- Bourns LM-NP-1001-B1
- Western Electric 111C
- Western Electric 119C
- Walters OEP8000
- Stancor TTPC-2
- Stancor TTPC-6
- Stancor TTPC-8
- Jensen DIN-2LI

The first three transformers are physically small (the red and yellow parts shown in the photograph) low-cost parts intended for telephone line isolation in telephone answering machines, fax machines and modems. The Tamura and Bourns parts are under US$ 5.00 each and the SP-70 is around $15 in single lot prices. These parts are available from the usual suppliers such as DigiKey and Mouser.

I studied the two Western Electric parts because I had them in my junkbox. They weigh several pounds each and have a reputation of being superb transformers. In the telephone network, these are used to isolate subscriber line drops from transmission circuits in a few special instances. (They are not and have not been used routinely in residential or business telephone service.) For example, many broadcast leased line program circuits historically used 111C and 119C coils. I use the term "coil" because both these parts bear the nomenclature "repeating coils," not transformers. I have no idea what these repeating coils cost. The 111C coil (in the oval case) was manufactured in 1956, whilst the 119C coil carries a 1972 production date. When these parts are available on E-bay, for example, the going price for a 111C coil is around $75 plus shipping.

Except for the 119C coil, are the tested parts are 600 ohm : 600 ohm transformers. (The 119C coil is 600 ohm : 520 ohm.)

Tamura TTC-108 Transformer

The TTC-108 is a small transformer for telephone interfaces aimed at the modem and fax market. The relevant specifications are reproduced below.

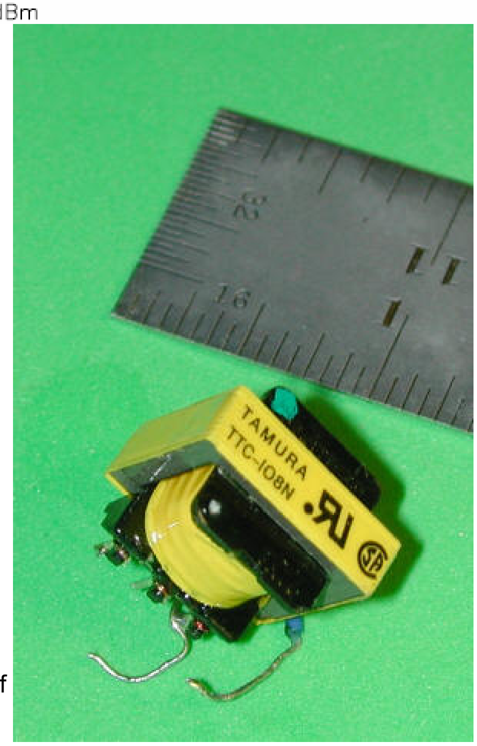
TELECOMMUNICATION DRY COUPLING TRANSFORMER DESIGNED TO OPERATE AT A MAX LEVEL OF +7dBm AND TO REFLECT A PRIMARY SOURCE IMPEDANCE OF APPROXIMATELY 600ΩCT WITH 600ΩCT LOAD ON SECONDARY

A. Electrical Specifications (@ 25° C)

1. Pri Source Impedance; 600Ω CT
2. Sec Load Impedance; 600Ω CT
3. Operating Level; −45 dBm to +7 dBm
4. Insertion Loss;
   1.4 dB MAX @ 1 KHz, 0 dBm
5. Frequency Response;
   ±0.5 dB 300 Hz to 3.5 KHz @ 0 dBm
6. Primary Impedance;
   600 Ω +15%, −5% @ 300 Hz to 3.5 KHz, 0dBm
   600 Ω +10%, −5% @ 500 Hz to 2.5 KHz, 0dBm
7. Longitudinal Balance;
   60 dB MIN @ 200 Hz to 1 KHz
   40 dBm MIN @ 4 KHz
8. DC Resistance;
   (1−3) = 44 Ω ±20%
   (4−6) = 56 Ω ±20%
9. Turns Ratio; (1−3) : (4−6) = 1 : 1.00 ±2%
10. Dielectric Strength;
   1500 Vrms 1 minute @ Pri to Sec, and Pri to Core
   1000 Vrms 1 minute @ Sec to Core
11. Total Harmonic Distortion;
   0.5% MAX @ 300 Hz to 3.5 KHz, 0 dBm

RoHS COMPLIANT

UL# E142035



The term ï¿½dry couplingï¿½ means that the TTC-108 specifications are based on zero DC current through the transformer.

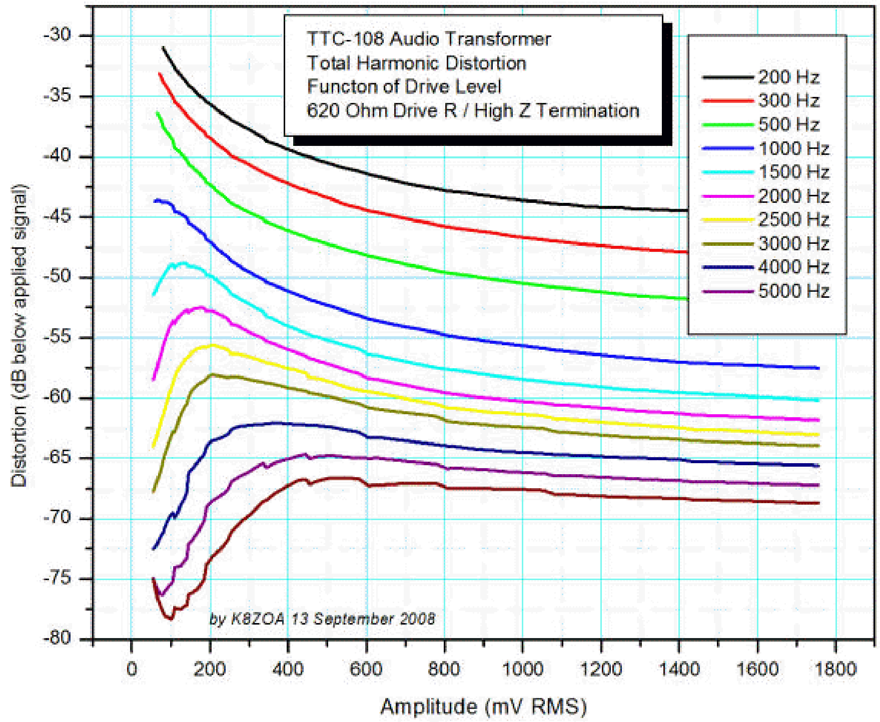
As discussed at Elecraft K3 Receive Audio, Elecraft's K3 uses a TTC-108 in both the left and right LINE OUT channels for ground loop isolation. As currently manufactured (mid September 2008) the K3 drives the TTC-108 primaries with 604 ohm series resistance.

For audio levels exceeding about 10 mV RMS, I've measured third harmonic distortion consistently around -45 dB from the carrier from the K3's LINE OUT port. Elecraft K3 Receive Audio has details.

An alternative assessment of non-linear transformer response is intermodulation distortion. My Elecraft K3 Receive Audio page has extensive intermodulation measurements of the TTC-108 transformer.

The HP8903B has a minimum input signal level of 50 mV RMS, so all the tests I've made start with 100 mV.

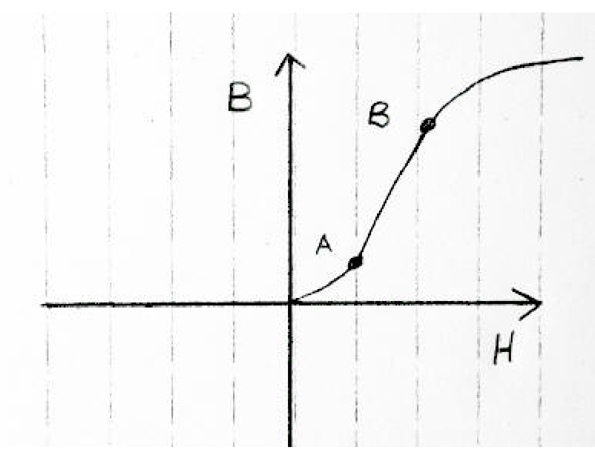
The plot below shows how THD varies as a function of frequency and output levels over the range 100 Hz - 6 KHz. This data is taken with the MCP-6021 op-amp driving source and 620 ohms series resistance between the op-amp output and the TTC-108 primary.



Tamura's data sheet quotes the TTC-108's THD as ï¿½less than 0.5%, 300 Hz ï¿½ 3.5 KHz at 0 dBm.ï¿½ 0 dBm at 600 ohms is 0.775 volts, and 0.5% THD corresponds to -46 dB. [THD quoted as a percentage is on a voltage basis and may be converted to dB with the formula THD_{dB} = 20*Log(THD%).] For 800 mV, the THD at 300 Hz is almost exactly -46 dB, meeting Tamura's specification on the money. At 3.5 KHz, the THD is about -62 dB down from the reference signal.

For frequencies commonly used with CW and data communications, say 500 Hz to 2500 Hz, the data is broadly consistent with the -45 dB figure I measured in the K3's output. However, note that there's a clear trend to lower distortion with higher output levels. Also, there's a marked turnover at lower amplitudes with frequency. Compare, for example, distortion at 50 mV and 200 mV. Below 1000 Hz, the distortion at 50 mV is greater than that at 200 mV, but above 1000 Hz, the distortion at 50 mV is less than at 200 mV.

If we look at a typical B-H curve, the reason for this effect can be ascertained. The sketch at the right shows a single valued B-H curve for simplicity. It is divided into three regions, origin to A, A to B and above B. These correspond to:



- Origin-to-Aï¿½reversible growth in domains. The relationship between B and H follows a cubic law relationship.
- A-to-Bï¿½irreversible growth in domains. This region is approximately linear.
- B-and-aboveï¿½rotation of the domains, gentler slope and not linear. At some point, B saturation occurs and the only increase in B is due to μ_0, *i.e.,* the incremental permeability is reduced to that of vacuum.

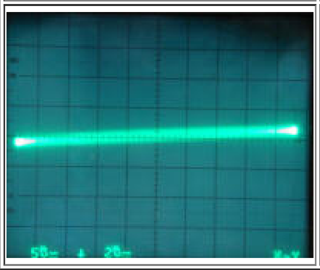
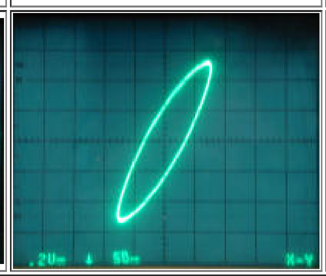
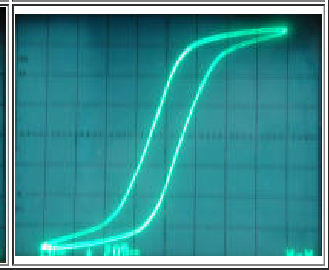
How does this relate to the distortion data?

As the signal amplitude increases, operation picks up more and more of the linear B-H curve. At any particular frequency, as the amplitude increases, more operation is in the linear portion, until the onset of saturation at point B on the B-H curve. Hence we see a decrease in THD as amplitude increases. This is true for all frequencies, once the ï¿½worst caseï¿½ THD frequency is passed.

On the reduced amplitude of the worst case frequency, a different mechanism is at work, where THD decreases with decreasing amplitude. This is related to the reversible growth region where the B-H curve is roughly cubic, *i.e.*, B is proportional to H^3. If H is small, then B is closer to linear than when H is greater. Accordingly, the smaller the applied voltage the smaller is the corresponding magnetic field H and the closer to linear is the relationship of B to H. Accordingly, we expect the THD to start at a lower level and increase as the applied voltage increases. This behavior is seen in the plot for 1500 Hz and higher frequencies. The reason it is not seen at lower frequencies is that the applied test voltage of 50 mV is not sufficiently low, at frequencies below 1500 Hz, to keep the H field ï¿½smallï¿½ enough to make its relationship with B even approximately linear.

The crossover point, or point of maximum THD, occurs where the magnetic flux B is so large as to place major parts of B near the cubic/linear transition point but no so large as to make major parts of B in the linear region.

The B-H plots below are all taken with a TTC-108 transformer at 150 Hz, with the test voltage as indicated above the image.

100 mV RMS	**2.2 V RMS**	**13.8 V RMS**
		

With 100 mV RMS applied at 150 Hz, the plot is at the limits of my oscilloscope's vertical gain to decently display the B field. Within the limits of the display, the B-H relationship looks quite linear.

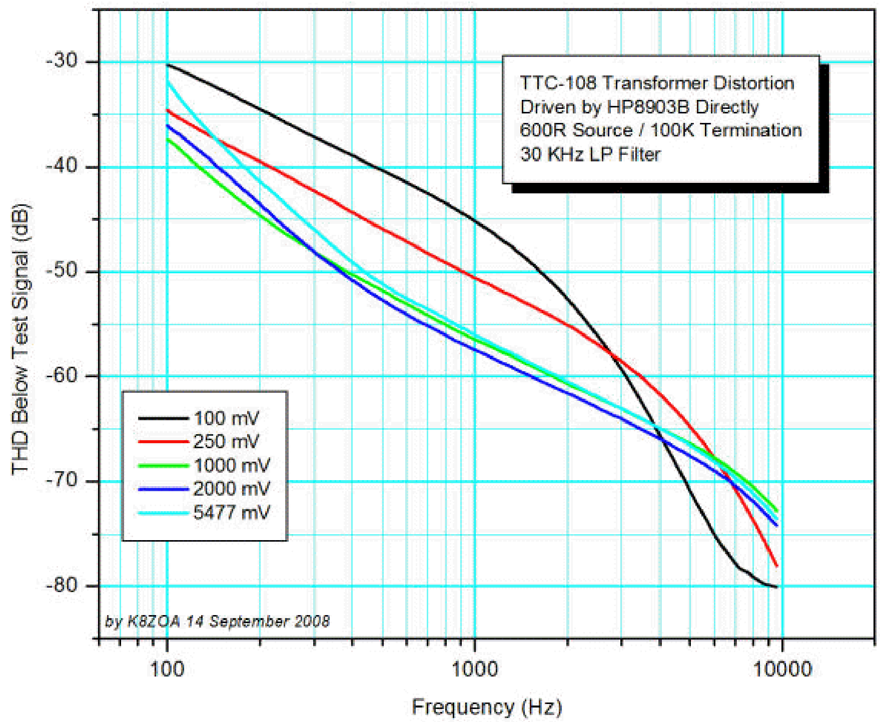
Increasing the applied voltage to 2.2V RMS (center image) shows a more interesting plot. There's no sign yet of saturation, but we see a clear non-linear relationship between B and H.

The right image applies 13.8 V RMS at 150 Hz to the TTC-108 transformer. It shows a clear knee but even at this level of magnetic field, total saturation has not quite been achieved.

Looking at the right hand figure, the knee point (point B in the sketch) is approximately 4 V RMS, well above the maximum test voltage applied in the center plot.

To see what happens when driven as hard as is possible with the 8903B analyzer, I ran a series of plots with just the transformer connected to the 8903B's audio generator section; the MCP-6021 op-amp circuit is not used in this plot.

The highest test voltage I used is 5.477 volts, corresponding to 50 milliwatts power into 600 ohms. At the lowest test frequency, 100 Hz, we see the distortion is clearly climbing, although not quite to the level seen at 100 mV, where the B-H curve is operating in the cubic law region. At 100 Hz and 5.477 volts, the B-H curve was being cycled past the knee region, but not too much into the non-linear area. As the test frequency increases, the B-H curve is not pushed to the knee region, even at the maximum test voltage.

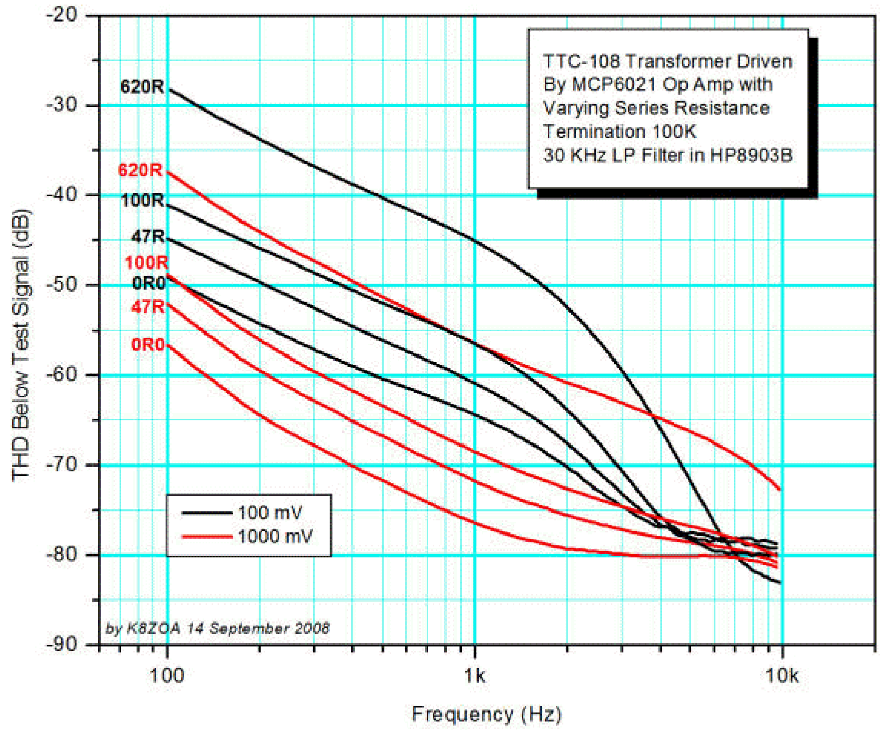


TTC-108 Distortion versus Driving Resistance

In the theoretical discussion section, I suggested that a zero ohm driving source would significantly reduce transformer distortion. Of course, it's not possible to have a true zero ohm driving source for two reasons. One is that all amplifiers have some output impedance, and, more importantly here, the transformer's winding resistance and leakage inductance form a minimum driving impedance. The output impedance of the MCP-6021 op-amp at audio frequencies for small signals is a fraction of an ohm, but the TTC-108's winding resistance (pins 1-3) is 44 ohms (56 ohms for the winding between pins 4-6).

The plot below shows measured THD when the TTC-108 is driven by the MCP-6021 op-amp buffer with one of four resistances between the MCP-6021 and the TTC-108:

- 620 ohms (the nearest 5% standard resistor value matching Elecrafts's 604 ohm series resistor used in the K3's LIN OUT audio circuit.)
- 100 ohms
- 47 ohms
- 0 ohmsï¿½direct connection from MCP-6021 output to TTC-108 primary.



The measured data confirms our theoretical analysisï¿½the lower the driving series resistance, the lower the measured THD. This is true for both high and low voltage levels. Removing the 620 ohm resistor and substituting a direct connection, for example, lowers distortion at 100 Hz by 20 dB.

TTC-108 Frequency Response

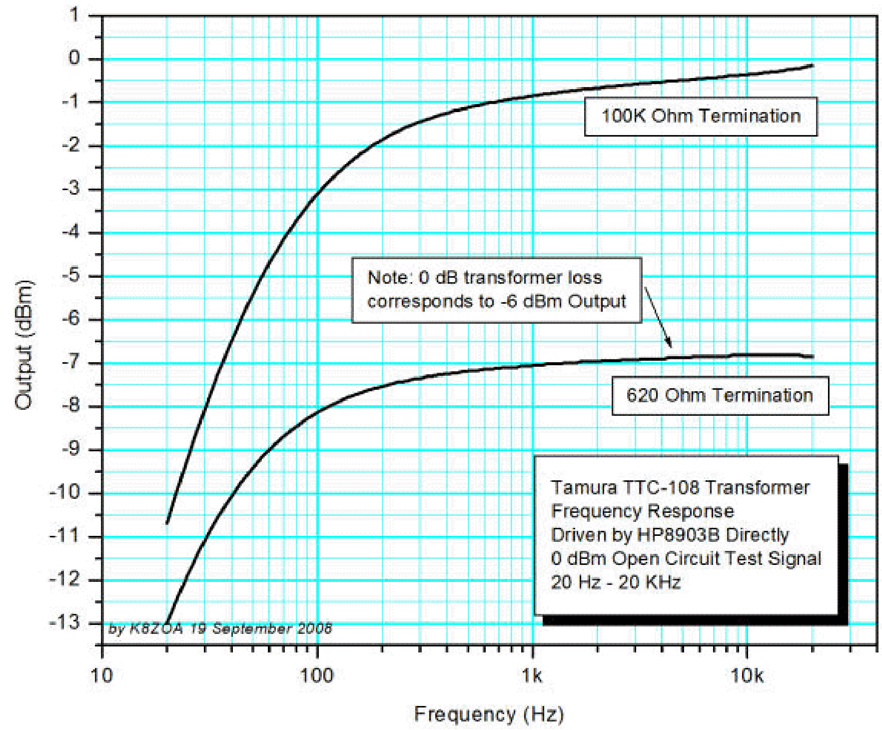
The plot below shows the TTC-108's frequency response over the range 20 Hz - 20 KHz, into a 620 ohm termination and into the 100 Kohm termination of the HP 9803B's analyzer section. In both cases, the 8903B's source is set to 600 ohms.

The test condition applies 0 dBm (775 mV) as measured into an open circuit. With a 620 ohm termination, therefore, zero insertion loss corresponds to 5.88 dB loss, so a perfect transformer will show -5.88 dBm output. Into a high impedance load, the theoretical insertion loss is effectively zero, so a perfect transformer will show 0 dBm output.

It's common to see a rising response when a transformer is terminated into a high impedance, due to winding capacitance resonance.

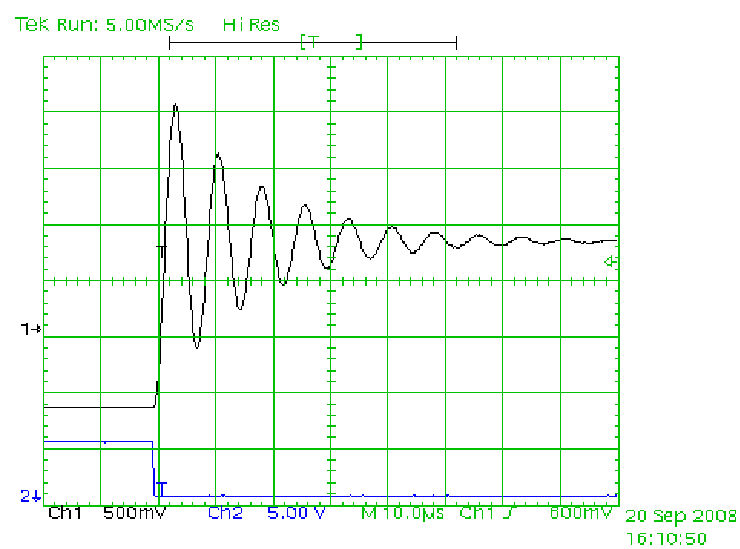
Tamura quotes the TTC-108 as being ±0.5 dB measured at 0 dBm from 300 Hz to 3.5 KHz, with an insertion loss of 1.4 dB (maximum) at 1 KHz, also measured at 0 dBm. This data is for the 600 ohm terminated case, of course.

The measured data shows an insertion loss of 1.0 dB at 1 KHz, and just under -0.5 dB at 300 Hz, so the TTC-108 meets its frequency response and insertion specifications.



TTC-108 Square Wave Response

The data shows moderate ringing only for the case of 50 ohm drive and high impedance termination. The ringing results from a dampened oscillation at the resonant frequency of the transformer secondary inductance and stray capacitance, including the test lead from the transformer to the oscilloscope. (The test does not use 10x probes, but rather a 6 ft length of RG-174 coaxial cable in an attempt to mimic how the transformer might be used in practice.) The ringing frequency is around 120 KHz.

<table>
<tr><td>50 Ohm drive, high impedance termination</td><td>
</td></tr>
<tr><td>50 Ohm drive, 620 ohm termination</td><td></td></tr>
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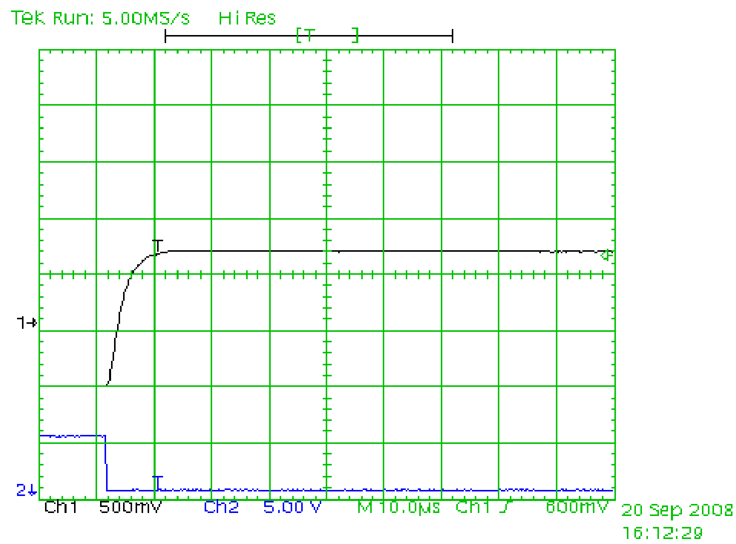
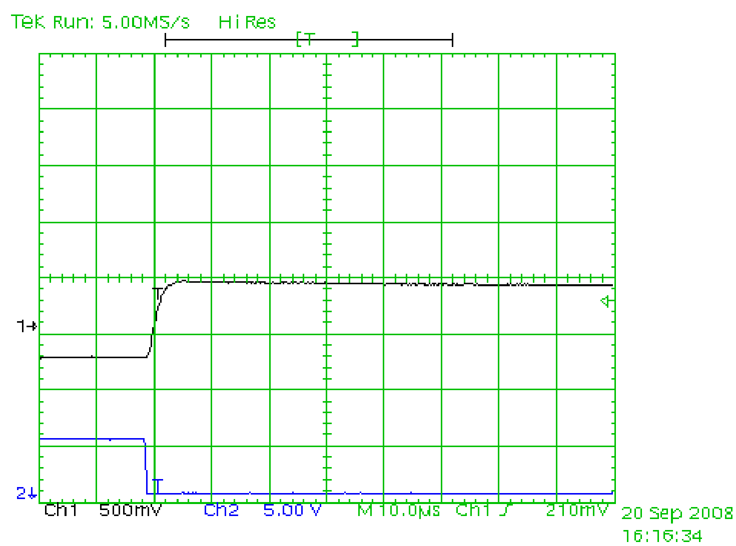
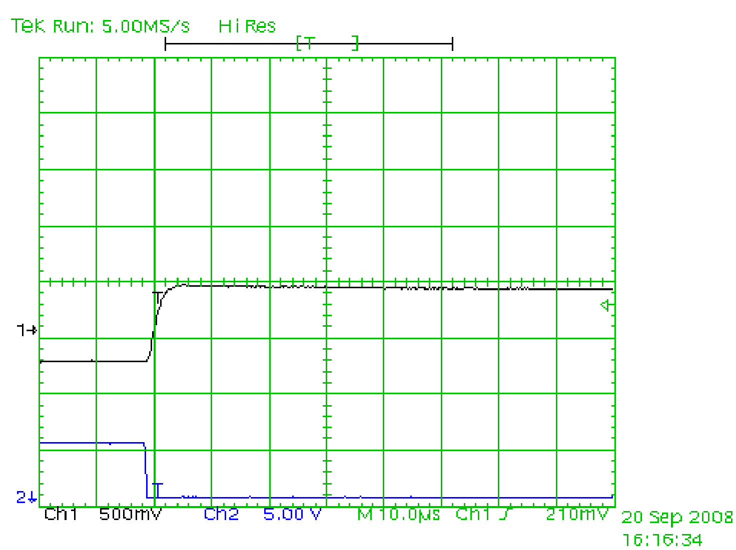
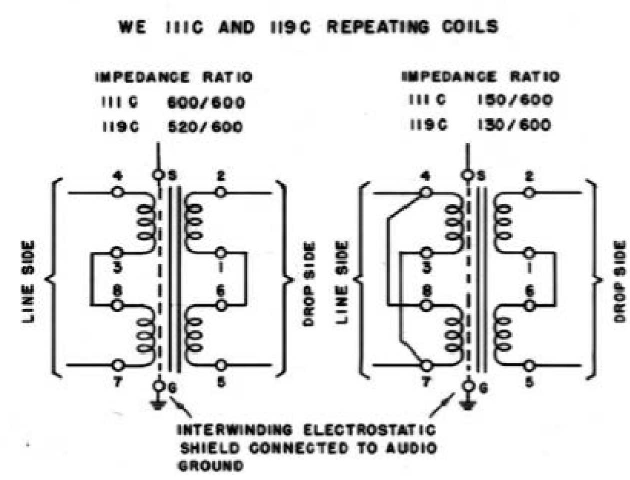
	
610 Ohm drive, high impedance termination	
610 Ohm drive, 620 ohm termination	

Western Electric ï¿½repeating coilsï¿½ have long had a reputation of low distortion. A ï¿½repeating coilï¿½ is a transformer in Bell System terminology. I have two WeCo repeating coils in my junk box:

- 111Cï¿½manufactured in the 1950's
- 119Cï¿½manufactured in 1972



Both the 111C and 119C repeating coils have split coil windings. The test configuration I used is 600:600 for the 111C coil and 600:520 for the 119C coil.

Specifications on these coils are hard to find, with frequency response and power levels about all that's available.

Since the Western Electric coils have a much wider frequency response than the other transformers examined on this page, I ran a distortion plot over the range 20 Hz ï¿½ 20 KHz, representing the traditional ï¿½high fidelityï¿½ frequency range. (These sweeps are with the 8903B's 80 KHz low pass filter engaged.)

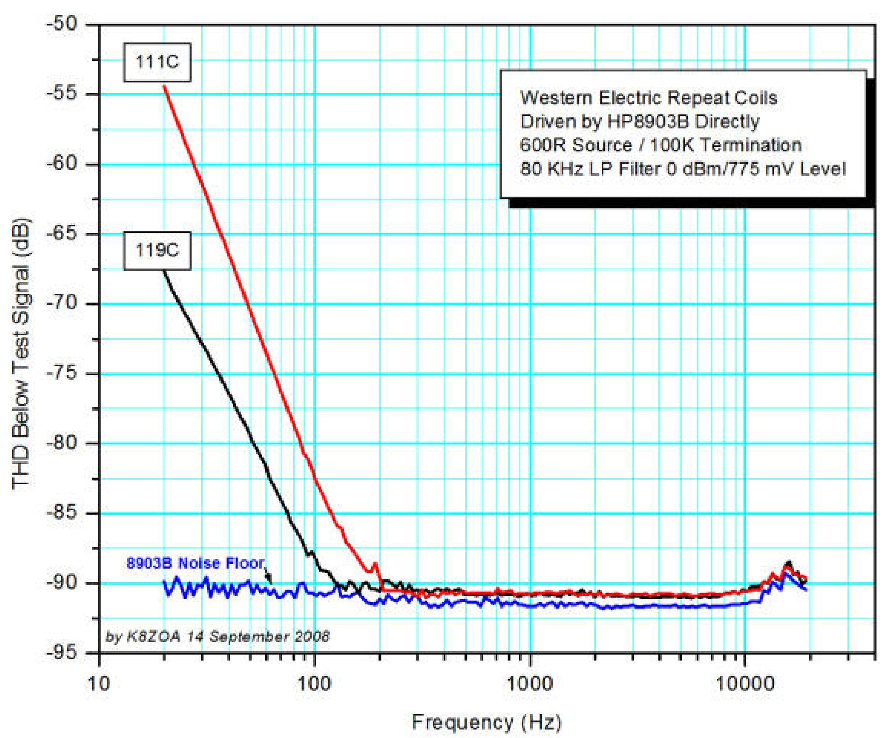
FREQUENCY RESPONSE
± 0.5 DB 30 TO 15,000 CYCLES

FOR IMPEDANCE MATCHING, ISOLATION, AND LINE-TO-LINE APPLICATIONS.

MAXIMUM LEVEL + 30 DBM AT 30 CYCLES

NOTE: DBM APPLIES TO A 1 MILLIWATT REFERENCE LEVEL ACROSS 600 OHMS

As the plot below demonstrates, neither of the Western Electric coils disappoint, with THD at or below my ability to measure for frequencies over 200 Hz.

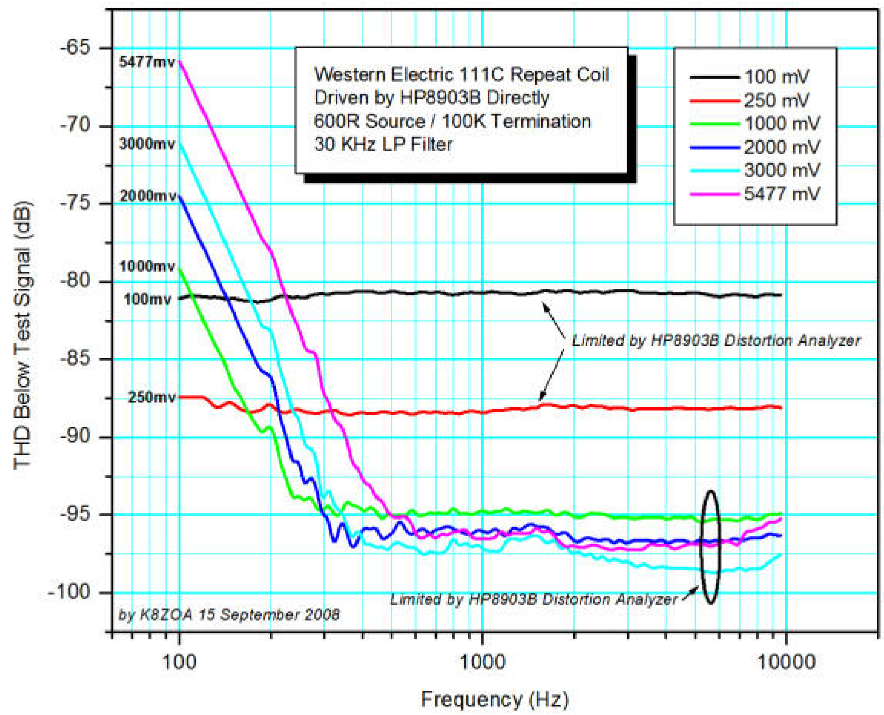


The newer 119C coil shows considerable improvement over the 111C coil at lower frequencies, being at my measurement floor until nearly 100 Hz and providing -65 dB THD at 20 Hz.

The test voltage applied, 775 mV, corresponds to 0 dBm at 600 ohms.

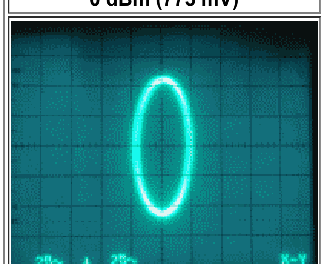
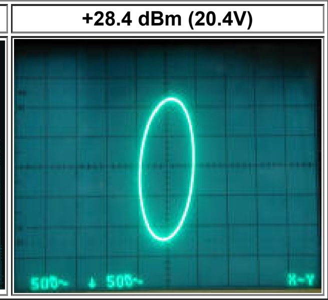
The plot below shows the 111C repeat coil with varying test voltages from 100 mV (-17.8 dBm) to 5477 mV (+17 dBm). At the two lowest voltage levels, 100 and 250 mV, the 111Cï¿½s THD is below the ability of my HP8903Bï¿½s ability to resolve. Likewise, at the higher test voltages, the THD is below the HP 8903B's resolution above 500 Hz or so.

I did not run a similar plot for the 119C coil, but, based upon the 0 dBm test, there's little reason to expect it to be anything but better than the 111C coil.



With higher voltage levels, THD can be seen, but even at +17 dBm, it disappears below the 8903Bï¿½s resolution at -98 dB. Above 600 Hz or so, the THD is at or below the distortion analyzerï¿½s floor.

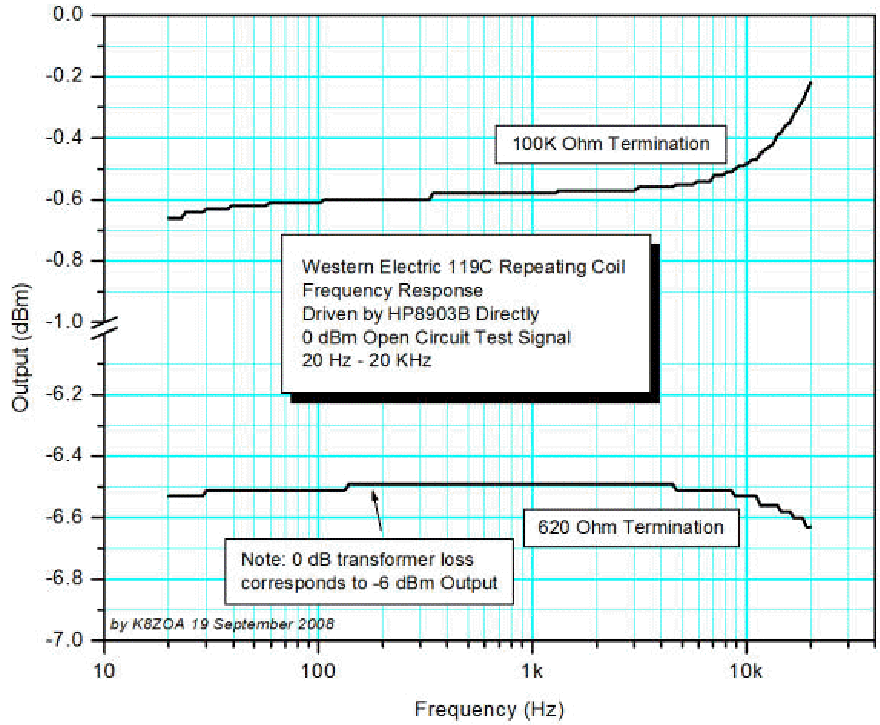
To see whether the excellent distortion performance results from a linear B-H curve, I ran two B-H curves on the 119C coil, one at 0 dBm (775 mV) and the second at the maximum output my HP 200CD oscillator could supply, 20.4 volts (+28.4 dBm) with the results displayed below.

0 dBm (775 mV)	+28.4 dBm (20.4V)
	

These B-H curves are remarkable. The shape of the curves are essentially identical. (Of course, the sizes are different; I've adjusted the oscilloscope's X and Y axis gain settings to keep the images on the screen.) In neither case is there even a hint of saturation. The 0 dBm curve has a fair bit of noise as the the signal is only a few millivolts. The right hand curve can be seen to just start to tilt to the right, but otherwise has a shape almost indistinguishable from the 0 dBm case. These B-H curves are not linear but they are highly symmetric and without discontinuities, which contribute to excellent THD performance.

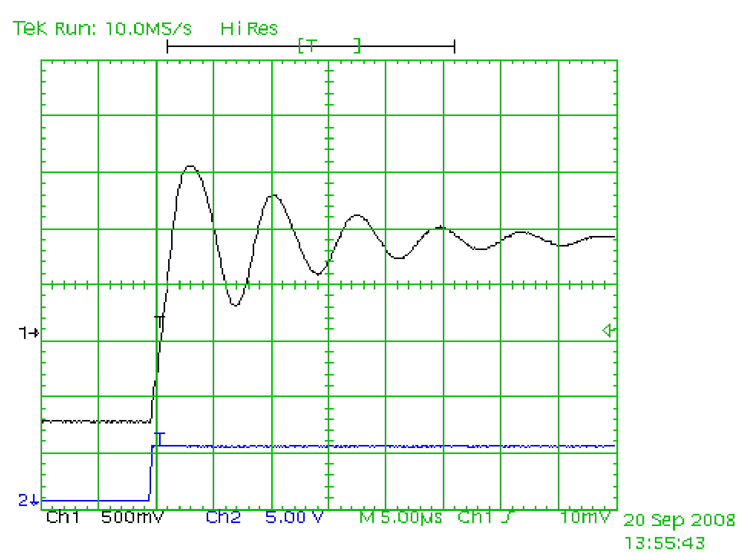
Western Electric 119C Repeating Coil Frequency Response

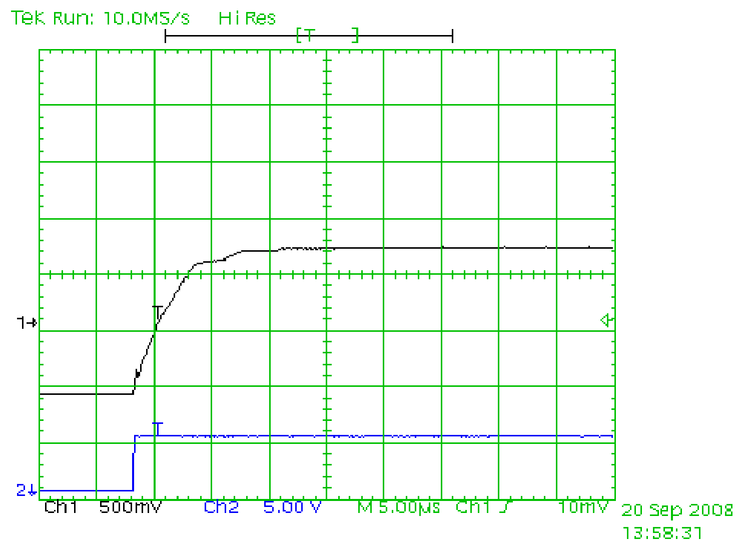
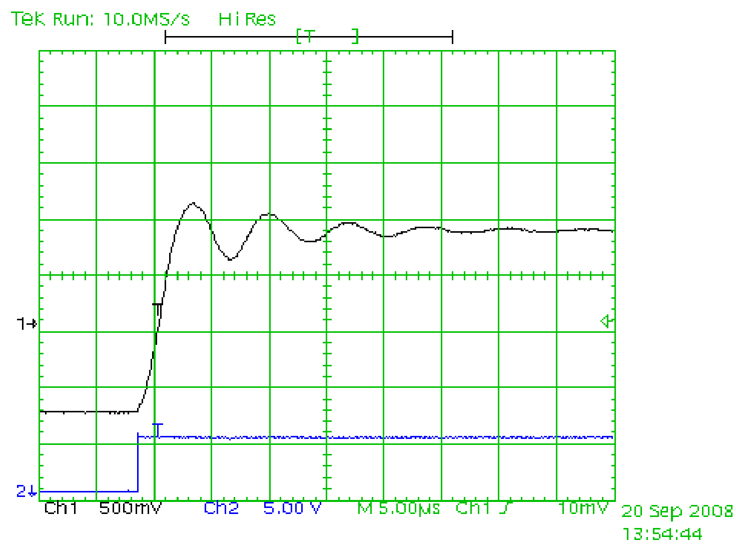
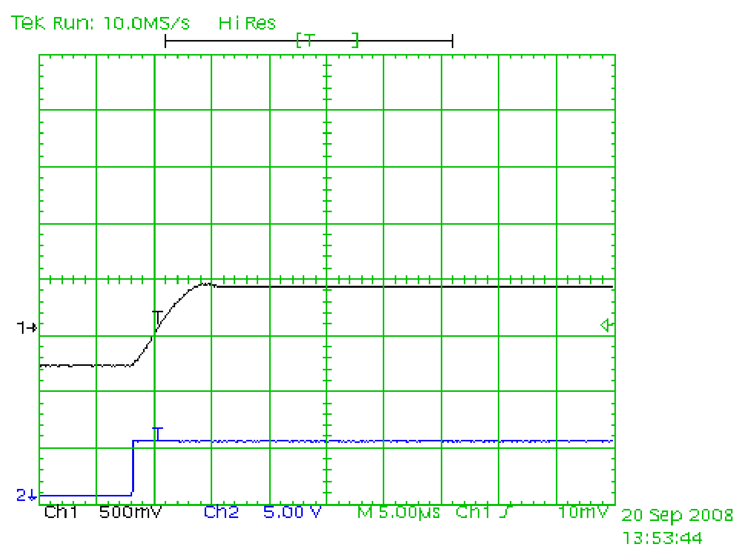
I ran a 20 Hz - 20 KHz frequency response sweep on the 119C coil, with the results shown below. With a 620 ohm termination, the response varied less than ±0.1 dB over the full 20 Hz - 20 KHz range, with an insertion loss around 0.5 dB. All in all, an excellent transformer, particularly considering the technology is 40 years or more old.



Western Electric 1 19C Coil Squar e Wave Response

The data shows moderate ringing for the case of 50 ohm drive and high impedance termination, and limited ringing for 620 ohm drive and high impedance termination. The ringing results from a dampened oscillation at the resonant frequency of the transformer secondary inductance and stray capacitance, including the test lead from the transformer to the oscilloscope. (The test does not use 10x probes, but rather a 6 ft length of RG-174 coaxial cable in an attempt to mimic how the transformer might be used in practice.) The ringing frequency is around 120 KHz.

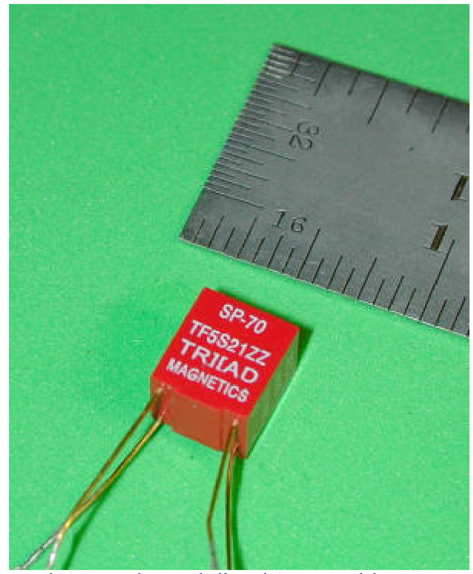
50 Ohm drive, high impedance termination	

50 Ohm drive, 620 ohm termination	
610 Ohm drive, high impedance termination	
610 Ohm drive, 620 ohm termination	

Triad SP-70 THD

I've used Triad SP-70 audio transformers with my Softrock Lite receivers after measuring several prospective candidates. It's a 600:600 ohm transformer, of roughly similar size to the

TTC-108. My web page



http://www.cliftonlaboratories.com/audio_transformer_data_and_modeling.htm provides considerable measured-versus-predicted data for the SP-70.

Triad provides a limited set of performance specifications for the SP-70:

Electrical Specifications (@25C)

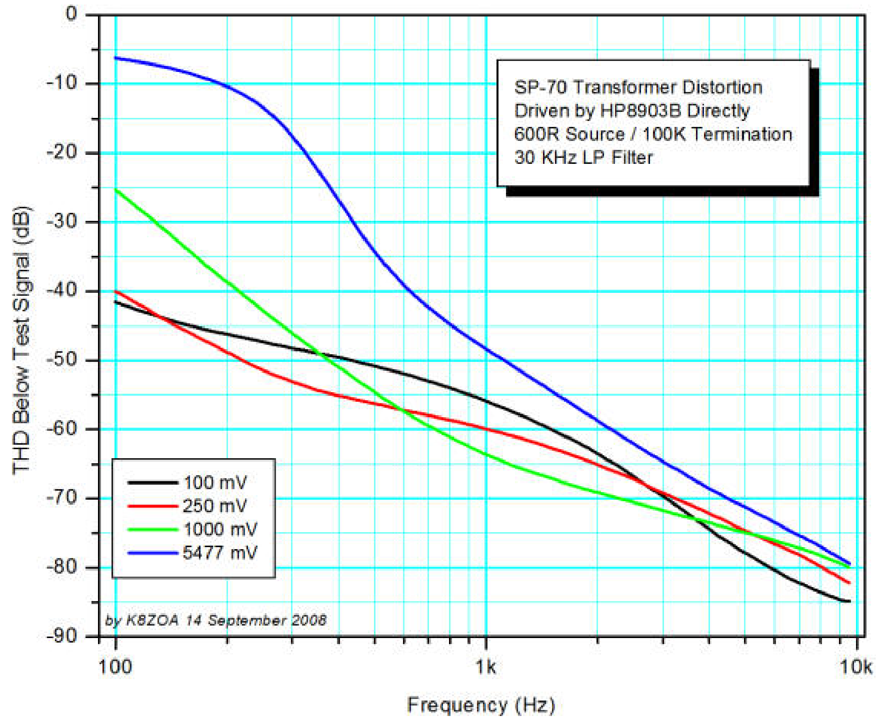
Power level (mW)	Matching Impedance		Max. Ma DC Unbalance in Primary	DC Resistance (Ω)		Overall Turns Ratio
	Primary	Secondary		Primary	Secondary	
50	600	600	3.0	72.0	92.0	1.0:1.0

Frequency Response: ± 2.0 DB, at 300 Hz to 100K Hz

Pri-Sec Hipot test (Pri-Sec): 1,000 VRMS for 1 sec.

Working voltage: 150VDC

Notably, Triad provides no distortion specification. I collected distortion data for the SP-70 by directly connecting the transformer to the HP 8903B distortion analyzer, without using the MCP-6021 op-amp driver.



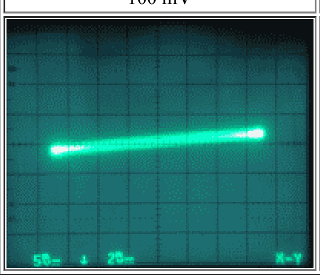
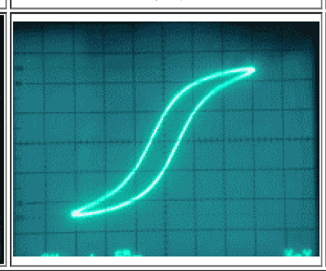
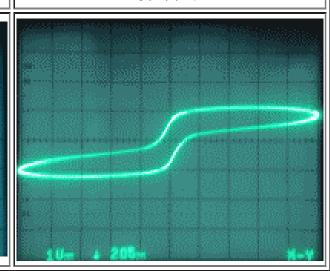
Looking at the lower signal level performance, at 100 mV and 250 mV RMS, the SP-70 provides lower THD than the TTC-108. At 500 Hz, for example, the SP-70 has 10 dB lower THD at 100 mV and likewise at 250 mV.

At higher signal levels, 1000 mV and 5477 mV, particularly at lower frequencies, however, something goes rather badly in the SP-70. At 100 Hz, for example, at 1000 mV, the SP-70 shows -25 dB THD, compared with -38 dB for the TTC-108.

One possible explanation for this behavior immediately springs to mindï¿½the SP-70 core is entering saturation at a much lower voltage than does the TTC-108, even though the SP-70 is rated at 50 mW (5477 mV at 600 ohms).

To verify this assumption, I ran three B-H curve on the SP-70 with the results shown below.

With 2.2 V RMS applied across the primary at 150 Hz, the core is well into non-linear operation and indeed not far from saturation at the tips of the B-H curve. Judging from the center portion of the 2.2 V B-H curve, with 1000 mV applied at 150 Hz the B-H curve is well into the non-linear region.

100 mV	2.2 V	5.477 V
		

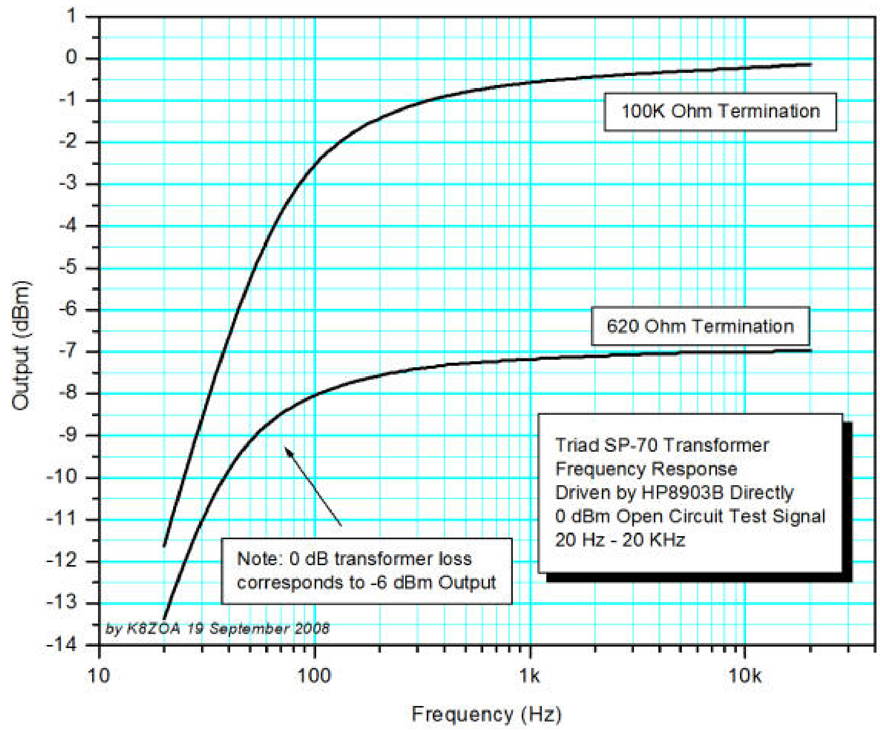
With 5.5 V RMS applied, the situation is even worse, as reflected in the right image. The core is deep into saturation. Note that B remains flat over large portions of H, *i.e.,* the core's magnetic elements are fully aligned with the H field and hence cannot amplify H. The consequence of a horizontal B-H curve is that the output waveform sags or flat tops or even decays. dB/dt is close to zero, so the induced secondary voltage is likewise close to zero. It's not surprising, therefore, that the THD is very high under these conditions.

SP-70 Frequency Response

The plot below shows the SP-70's response under the same test conditions as used for earlier frequency response sweeps.

Triad rates the SP-70 as ±2 dB from 300 Hz to 100 KHz. (I've provided plots out to 100 KHz on my http://www.cliftonlaboratories.com/softrock_lite_6_2.htm page, should you be interested in seeing the full range data.

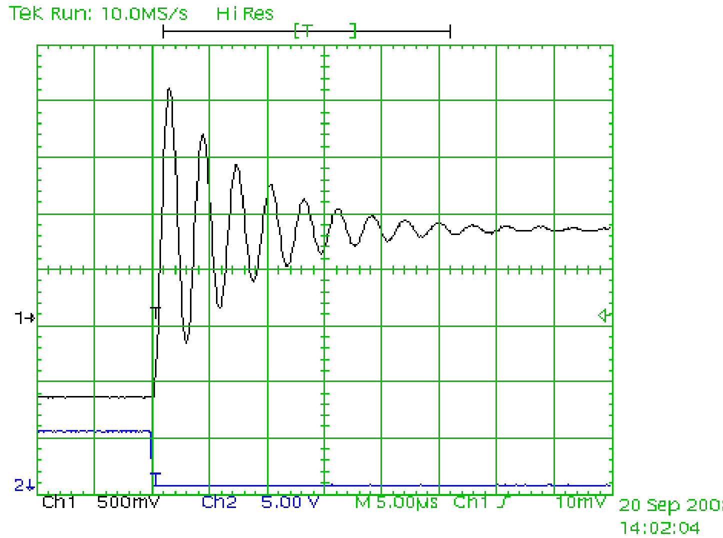
At 300 Hz, the SP-70 is down about 0.5 dB from the 1000 Hz value, so it easily meets the published low frequency response specification. Triad does not provide an insertion loss specification, but the measured data shows about 1 dB, which is quite typical of this size transformer.



SP-70 Squar e Wave Response

The data shows moderate ringing for the case of 50 ohm drive and high impedance termination, and limited ringing for 620 ohm drive and high impedance termination. The ringing results from a dampened oscillation at the resonant frequency of the transformer secondary inductance and stray capacitance, including the test lead from the transformer to the oscilloscope. (The test does not use 10x probes, but rather a 6 ft length of RG-174 coaxial cable in an attempt to mimic how the transformer might be used in practice.) The ringing frequency is around 330 KHz, a considerably higher frequency than seen in the Bourns or Tamura transformers.

50 Ohm drive, high impedance termination	

<table>
<tr><td></td><td>
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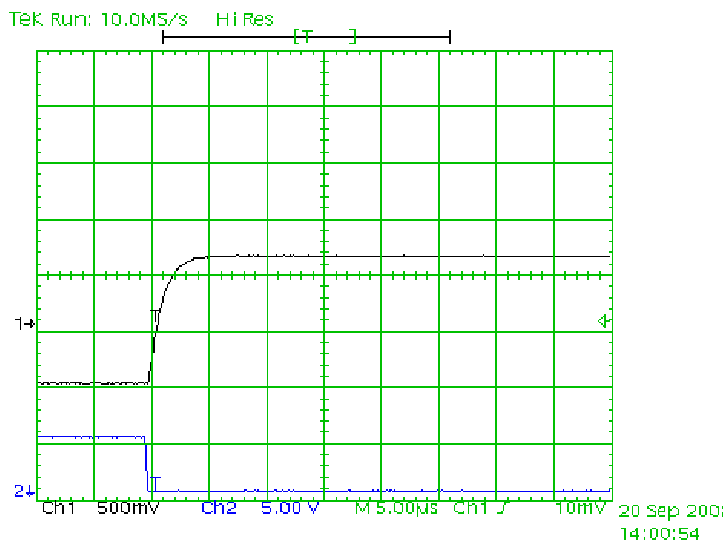
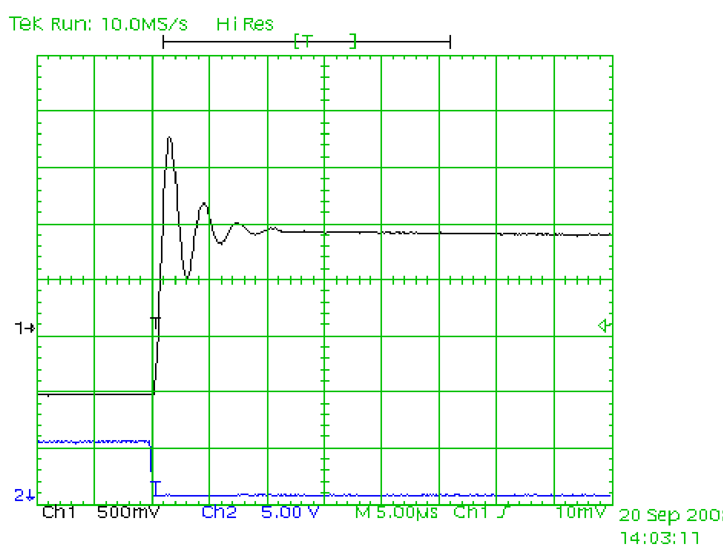
<tr><td>50 Ohm drive, 620 ohm termination</td><td>
</td></tr>
<tr><td>610 Ohm drive, high impedance termination</td><td>
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<tr><td>610 Ohm drive, 620 ohm termination</td><td></td></tr>
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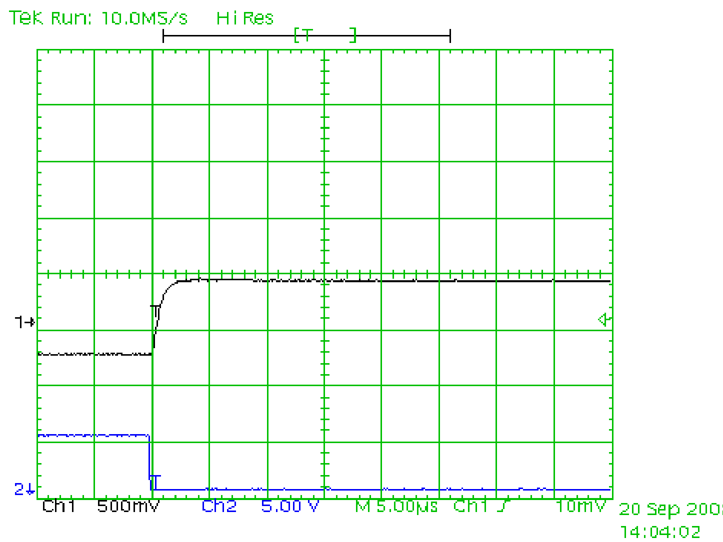
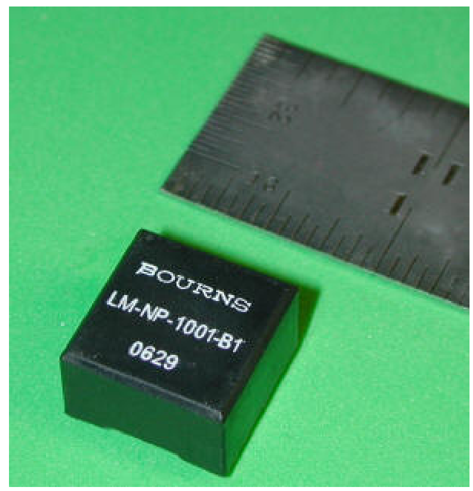


Bourns LM-NP-1001-B1 THD

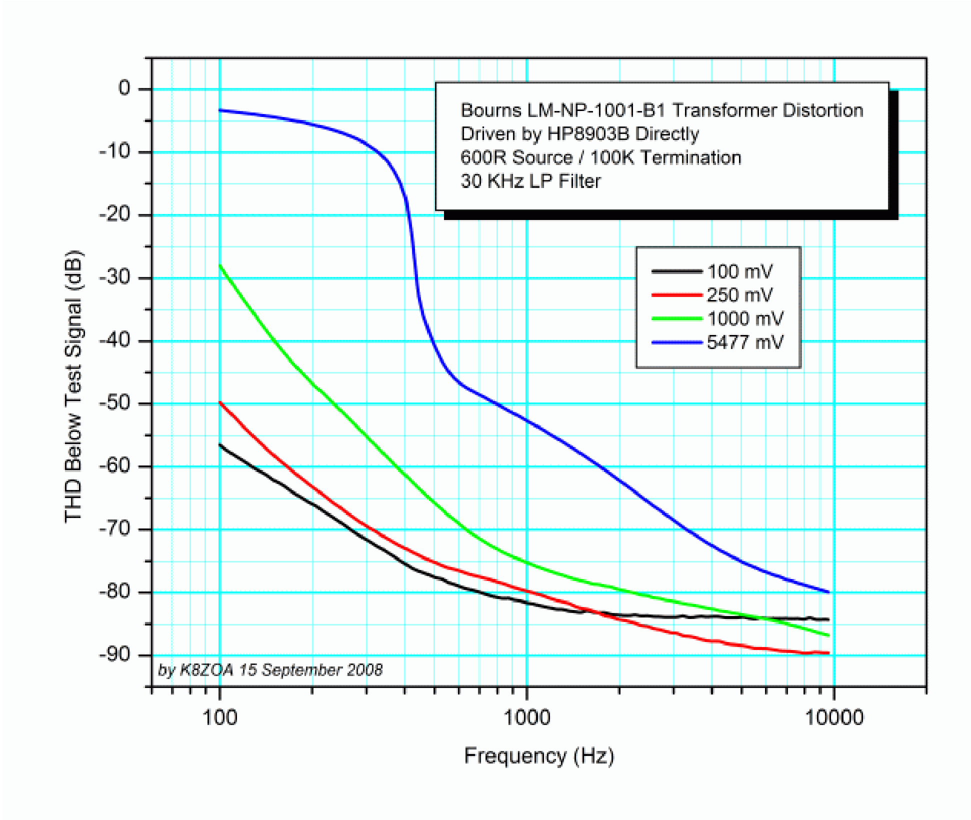


The Bourns LM-NP-1001-B1 transformer is aimed at the same market as the TTC-108, modems, faxes and other devices that connect to telephone lines. The transformer has a recommended operating impedance of 600 ohms, with the following other specifications of interest.

Compared with the TTC-108, the LM-NP-1001 has a wider frequency range and lower quoted distortion, 0.1% versus 0.5%. (0.1% distortion is -60 dB from the fundamental.) Note, however, that Bourns is playing ï¿½specsmanshipï¿½ as the quoted value is for 1 KHz, where we expect the THD to be low, whilst Tamura's 0.5% THD rating applies over the entire frequency range 300 Hz ï¿½ 3.5 KHz, a more stringent specification.

Frequency Response (typ./0.2 - 3.5 kHz)	dB	- 0.3
Wide Band Response (0.2 - 10.0 kHz)	dB	- 2.5
Power Level	dBm	- 45.0 to + 3.0
Longitudinal Balance (0.3 - 4.0 kHz)	dB	-80.0
Distortion (0 dB/at 1.0 kHz)	%	≤ 0.1
Leakage Induction (typical)	mH	14.0

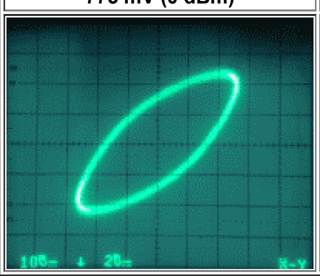
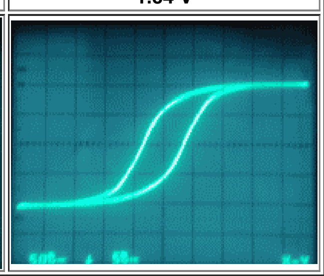
Regardless of whether Bourns was engaging in specsmanship with the 0.1% THD figure, as the plot below demonstrates, the LM-NP-1001 provides better THD performance at 100 and 250 mV than either the SP-70 or the TTC-108 parts. Indeed, at 100 Hz and 100 mV, the LM-NP-1001 has a THD of -56 dB, compared with -40 for the SP-70 and -31 for the TTC-108. Quite a remarkable improvement.



Bourn's data sheet quotes 0.1% (-60 dB) THD at 1 KHz with a 0 dBm test signal. The data shows THD at 1000 mV (+2.2 dBm) running at -75 dBm, more than comfortably over the quoted performance.

There's more of a problem, however, at lower frequencies, with the THD being only -29 dBm at 100 Hz. And, thereï¿½s a gross problem at 5477 mV, which at +17 dBm, is admittedly way over the transformerï¿½s +3 dBm maximum rating.

As usual, when we see high distortion, the B-H curve will help us understand what is going on.

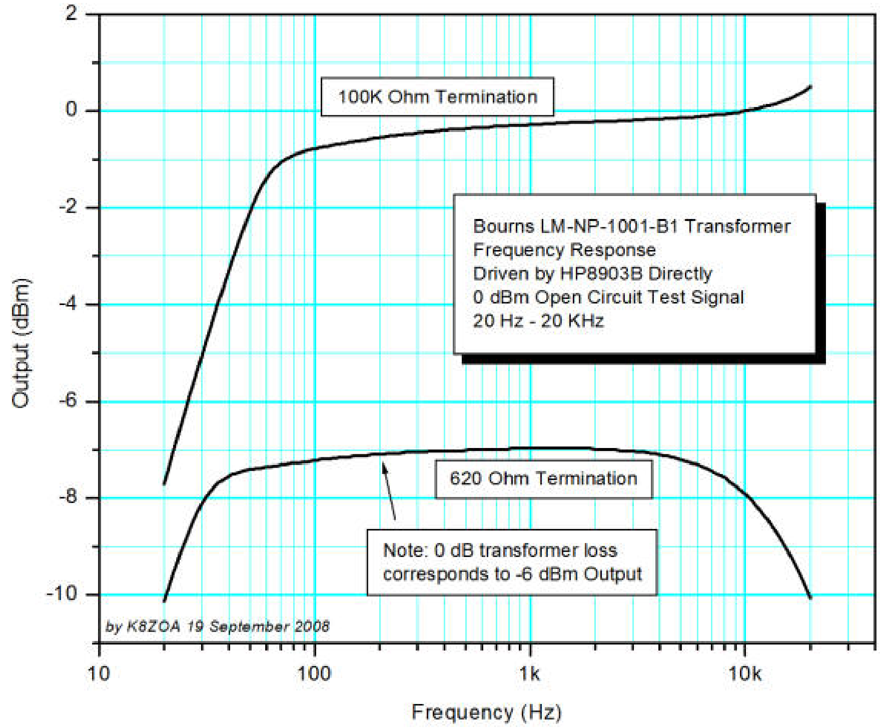
775 mV (0 dBm)	1.84 V
	

The B-H image at the left is the LM-NP-1001 with 775 mV RMS(0 dBM) test voltage at 150 Hz. It shows reasonable linearity over perhaps half the horizontal (H field) range, some distortion at the extremities. The THD under these conditions is around -40 dB.

The left image applies 1840 mV RMS to the LM-NP-1001 transformer. The tips of the B-H curve show severe saturation, and indeed saturation occurs over a major part of the H range. This behavior certainly explains the gross distortion seen at 5477 mV in the earlier plot.

Bourns LM-NP-1001-B1 Frequency Response

The plot below shows the LM-NP-1001-B1's response under the same test conditions as used for earlier frequency response sweeps.



Bourns quotes the frequency response range as -0.2 dB from 300 Hz to 3500 Hz, which the test sample easily meets.

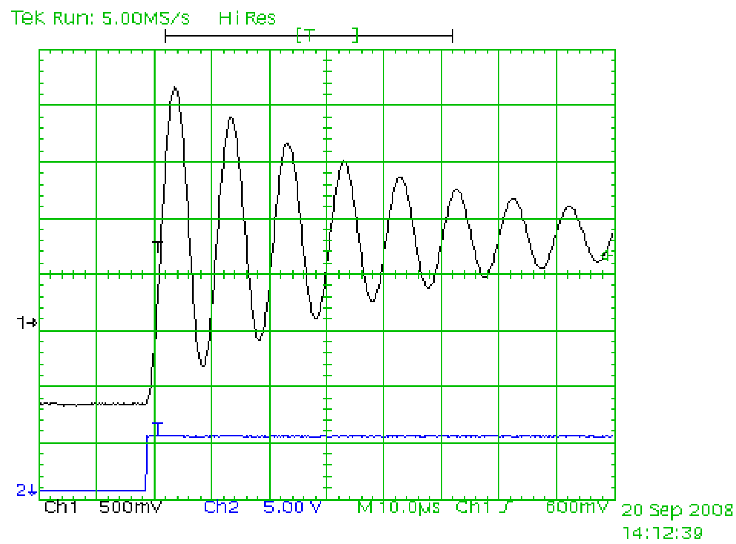
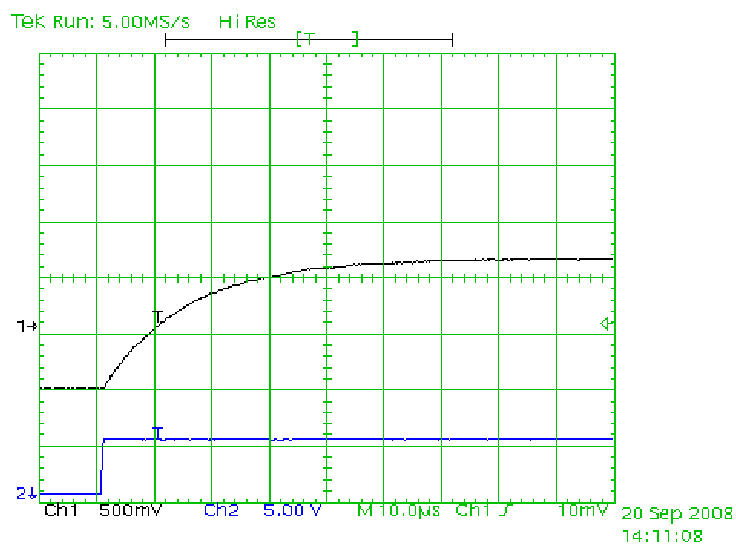
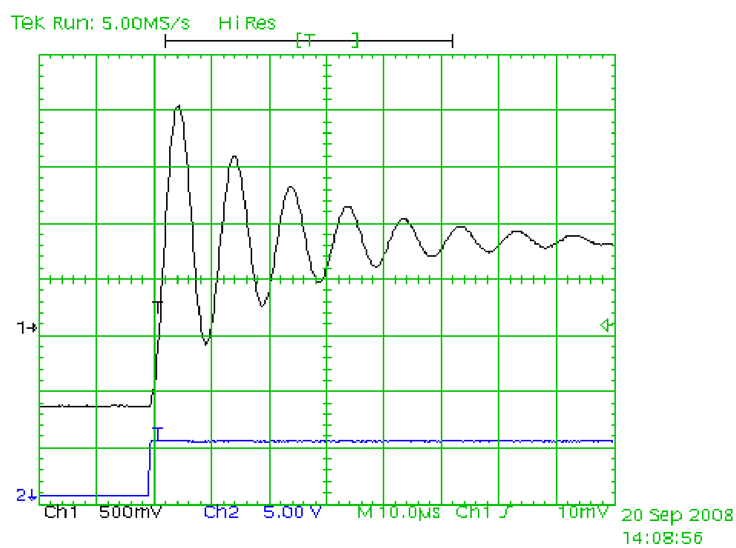
The insertion loss is quoted as "less than 1.5 db at 2 KHz" which again it easily meets, being about 1.0 db at this frequency.

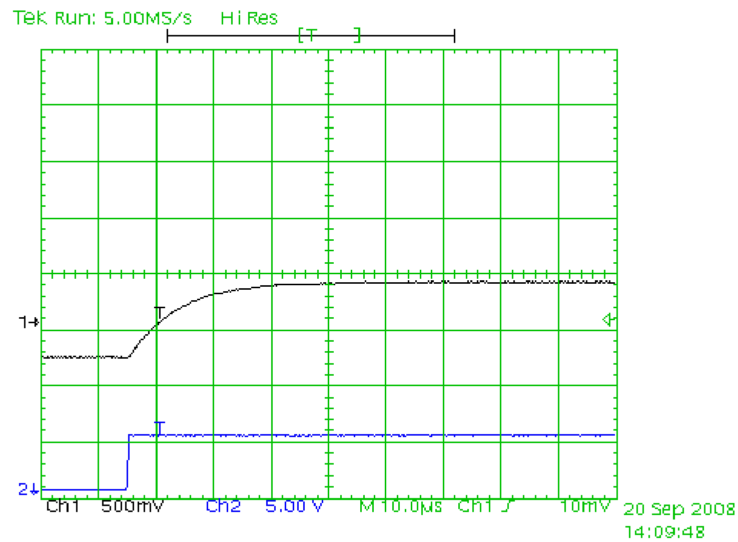
Bourns LM-NP-1001-B1 Square Wave Response

The data shows severe ringing when driven either with 50 or 610 ohms and high impedance termination. The ringing results from a dampened oscillation at the resonant frequency of the transformer secondary inductance and stray capacitance, including the test lead from the transformer to the oscilloscope. (The test does not use 10x probes, but rather a 6 ft length of RG-174 coaxial cable in an attempt to mimic how the transformer might be used in practice.) The ringing frequency is around 100 KHz.

The ringing is eliminated with 620 ohm termination regardless of the drive impedance.

50 Ohm drive, high impedance termination	

	
50 Ohm drive, 620 ohm termination	
610 Ohm drive, high impedance termination	
610 Ohm drive, 620 ohm termination	



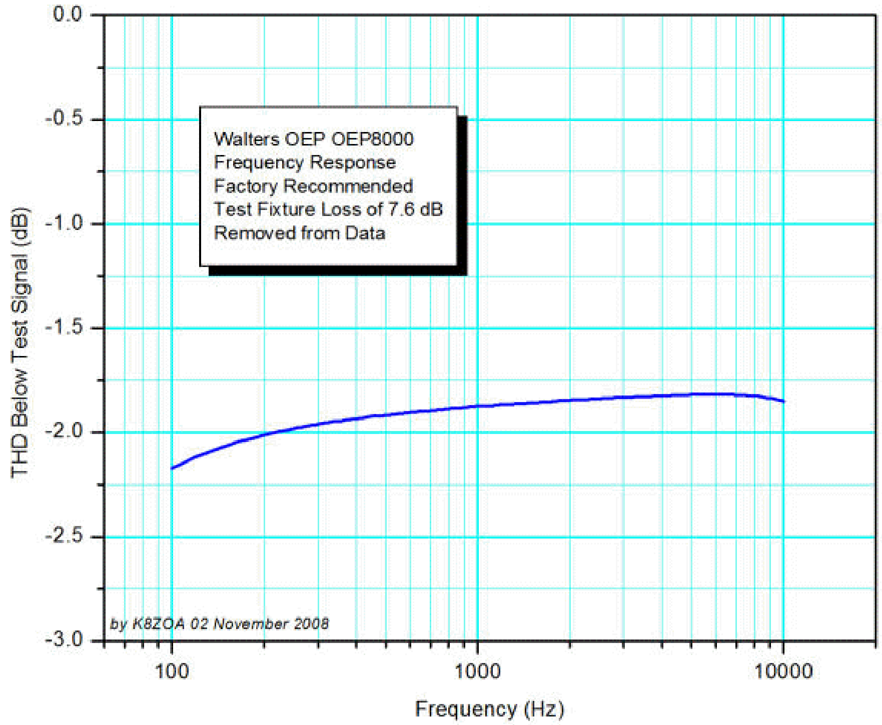
Walters OEP8000 Frequency Response

The OEP8000 is a physically small, surface mount 600 ohm : 600 ohm transformer designed for telephone coupling and similar applications, manufactured by Walters OEP Ltd., in Oxfordshire, UK. It may be purchased in the United States from Newark Electronics for $5.81 in single-lot quantities, or through Farnell in the UK. When purchased from Newark, the OEP8000 is shipped from Farnell (Newark acquired Farnell several years ago) and a $20 service charge instead of international freight shipping is applied.

The OEP8000's electrical specifications are reproduced below. I've highlighted the most intriguing speciï¿½THD of -89 dBm when 0 dBm is applied. In the distortion section of this analysis, we'll see that this specification must be read quite carefully however.

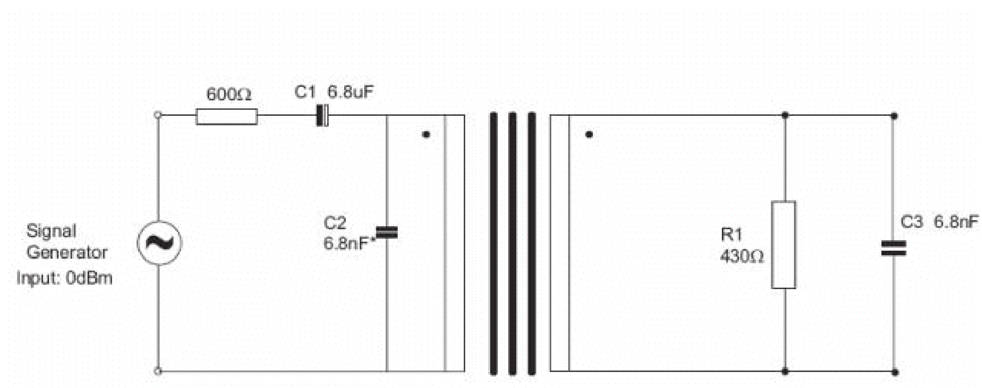
> Electrical specification:
>
> Ratio: 1 to 1
> Primary DC resistance: 111 ohms +/- 15%
> Secondary DC resistance: 111 ohms +/- 15%
> Impedance matching: 600 ohms to 600 ohms
> Inductance (270mVrms, 100Hz parallel) Pins 1 - 3: 3.6H min.
> Leakage inductance: (10mVrms, 200Hz series) pins 1 - 3: 4.1mH nom.
> Return loss: (ref. 600 ohms) 200 to 4kHz: -18dB min.
> Insertion loss: (ref. 600 ohms, 2kHz): 4dB max.
> (ref. 430 ohms, 2kHz): 2dB max.
> Frequency response: 200 - 4kHz: +/- 0.2dB
> Longitudinal balance: 200Hz - 4kHz: 80dB min.
> Turns ratio (@ 6kHz, 0.1Vrms), pins 1 - 3 & 6 - 4:1.00+/- 1%
> Distortion: 600Hz, 0dBm: -89dBm nom.
> Saturation: <10Vrms, 65V peak, 50Hz
> Hi-pot, primary to secondary: 3.3kV min., 1mA for 1 minute
> Operating temperature range: -10 to +85 C
> Storage temperature range: -40 to + +125 C
> Certified to EN60950-1: 2001
> RoHS compliant.
>
> Note: Do not pass DC current through windings.

The plot below shows the OEP8000's frequency response when tested in the factory recommended test fixture. The factory-recommended test fixture introduces about 7.58 dB excess loss into the data, so I've subtracted that from my measured value to derive the transformer's net insertion loss. The specification is 4 dB maximum at 2 KHz, and my data shows this to be comfortably met. The overall frequency response from 100 Hz to 10 KHz is relatively flat, with less than 0.5 dB variance over this range.



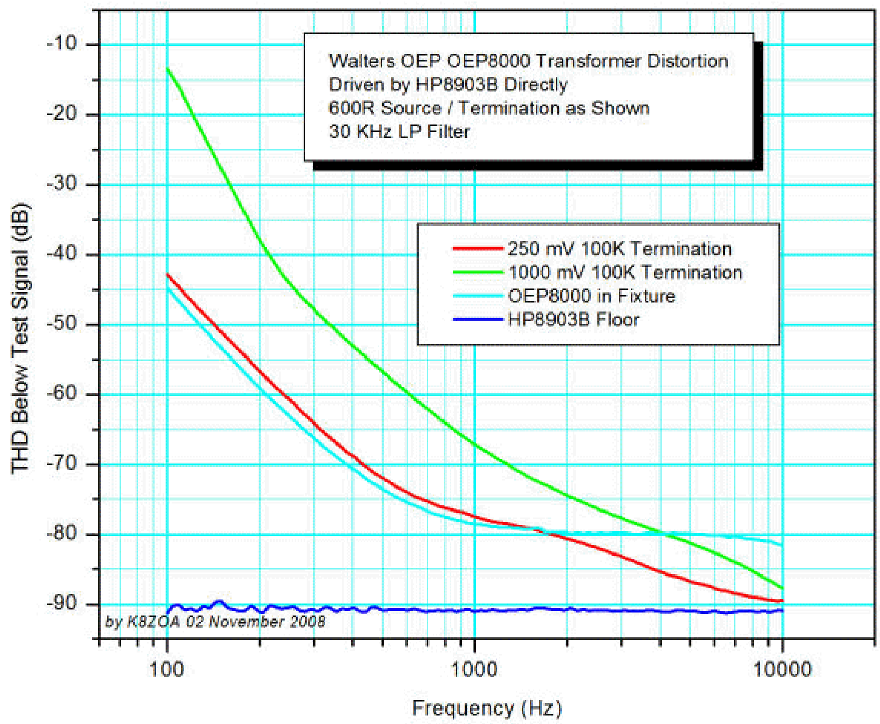
OEP8000 Harmonic Distortion

The schematic below is the recommended test fixture for the OEP8000 and I used it for the frequency response data above and the THD data presented below. I believe the secondary loading of 430R paralleled with 6.8 nF represents a typical British Telecom analog subscriber telephone loop impedance. The 6.8 uF capacitor on the primary side must be to block DC from the windings.



If the OEP8000 is replaced by a perfect 1:1 transformer, over most of the normal audio frequency band, the result of the test fixture is a resistive voltage divider, a perfect audio signal source and a 430 / (430 + 600) resistive voltage divider, resulting in 7.6 dB loss. At 1 KHz, the 6.8 nF capacitors have a reactance of 23 Kohm, and may be disregarded in this analysis. Likewise, the 6.8 uF series capacitor has a very low reactance at 1 KHz and may also be disregarded. These approximations become less accurate as the frequency increases, but are good enough through 3 or 4 KHz.

One point of concern is that the shunting capacitors will roll off high frequency signals, thus reducing the measured harmonic distortion where the test frequency is above a few KHz. As seen below, however, the measured data shows no sign of that effect.



The THD plot above show four measurements. The blue curve is the noise floor of the HP8903B analyzer with a coaxial cable between the generator output section and the analyzer input section, shunted with 430 ohms resistance and 6.8nF capacitance, so as to duplicate the factory test fixture loading. The applied signal generator voltage in this test was adjusted to deliver 261 mV to the analyzer's input, which is the voltage seen on the output side of the The instrument is capable of -90 dB THD at this voltage level.

The green and red traces are run using the same protocol as the other THD measurements on this page. The transformer's secondary is terminated with the HP8903B's analyzer input stage, which is 100 -Kohm. The cyan plot is the THD measured with the OEP8000 mounted in the test fixture. The HP8903B's signal generator section is set to deliver 0 dBm (775 mV) open circuit, with 600 ohm output impedance. When connected to the transformer and fixture, the actual voltage delivered to the 8903B's analyzer section is around 261 mV.

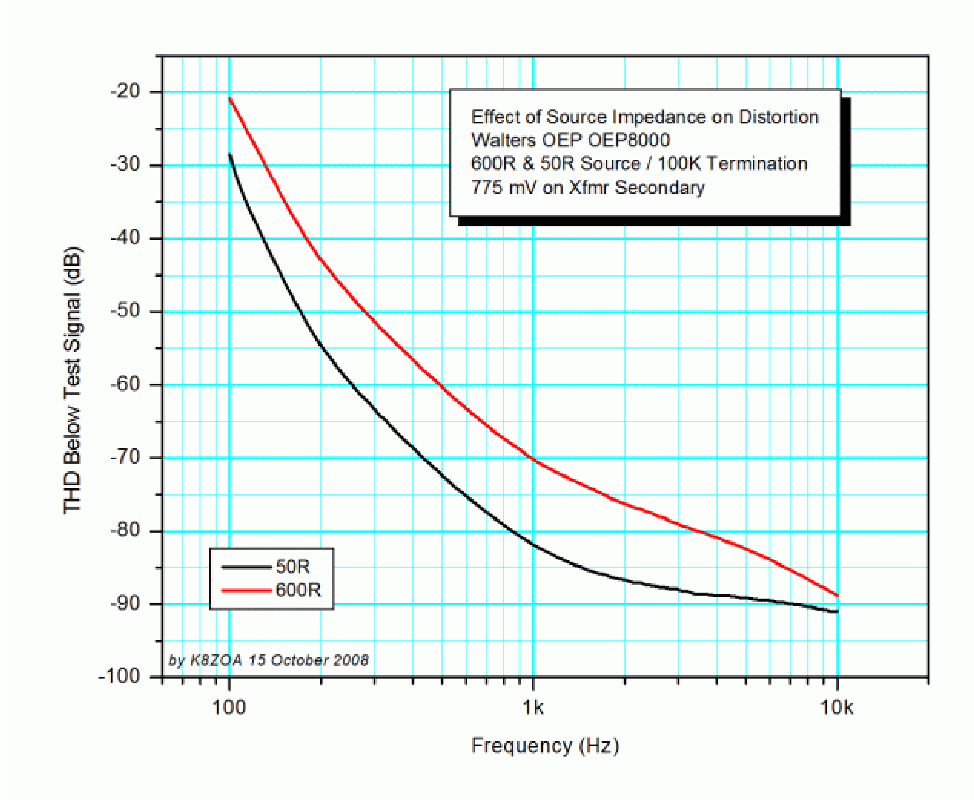
At the specified 600 Hz test frequency, in the test fixture, the measured THD is -75.4 dB *with respect to the 600 Hz signal level at the 8903B analyzer input section*. The measured 600 Hz signal level was 260 mV. We may therefore compute the total THD voltage as 260 mV * $10^{-75.4/20}$ or 44.1 microvolts. In an instrument reading voltage, but calibrated in terms of power delivered at 600 ohms, the resulting power is 3.25×10^{-12} watts or -84.9 dBm.

Measured this way, we might say that the THD is -85 dBm, which compares reasonably well to the OEP8000's quoted specification of -89 dBm nominal. The 4 dB discrepancy is likely subsumed within the "nominal" terminology.

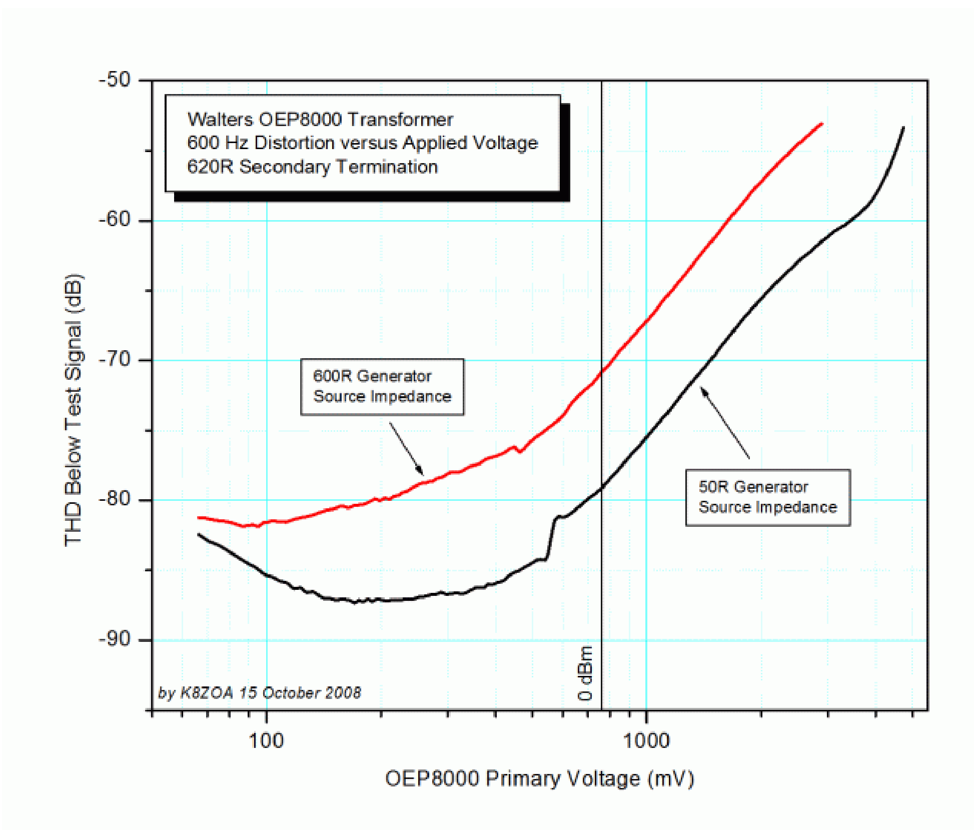
However, in my personal view, quoting THD as a dBm level is more an attempt to make the product look better than to enlighten the purchaser. It's far more common to quote TDH as a percentage of the output or X dB down from the output. In fact, the OEP8000 is the only transformer of the dozen or so I looked at that quotes an absolute value for THD. And, there's no need to embellish the OEP8000's distortion figures by "specsmanship" as it is quite a good performing transformer.

I should also add that dBm measurements presuppose a specific impedance, usually 50 ohms for RF and 600 ohms for audio. Since the voltage in the test circuit is being developed across 430 ohms (ignoring the shunt capacitance) it is not correct to refer to any measured voltage level in dBm where the reference level is (as is almost certainly the case) 600 ohms. I realize common usage often ignores the impedance into which a dB referenced value is measured, but ignoring the impedance does not make the usage correct.

I also measured distortion in the OEP8000 with 600 and 50 ohm driving source impedances into 100K termination. As with the other transformers examined, lower driving impedance improves the distortion considerably.



Finally, I swept the voltage at an applied 600 Hz frequency with both 50 and 600 ohm driving source impedance, with the results shown below. These datasets are with 620 ohm termination on the transformer secondary.

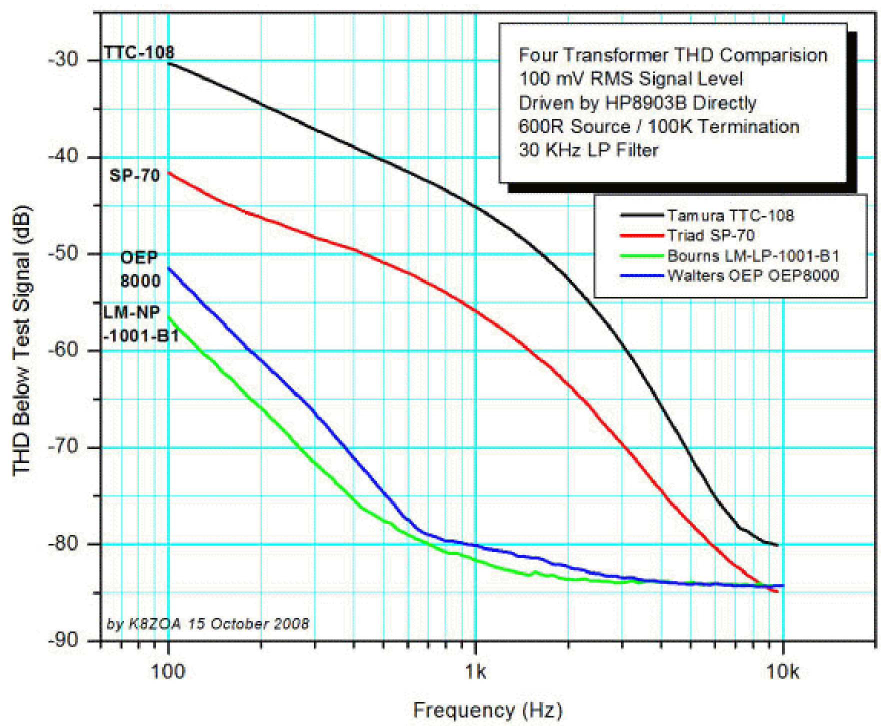


Comparisons and Conclusions

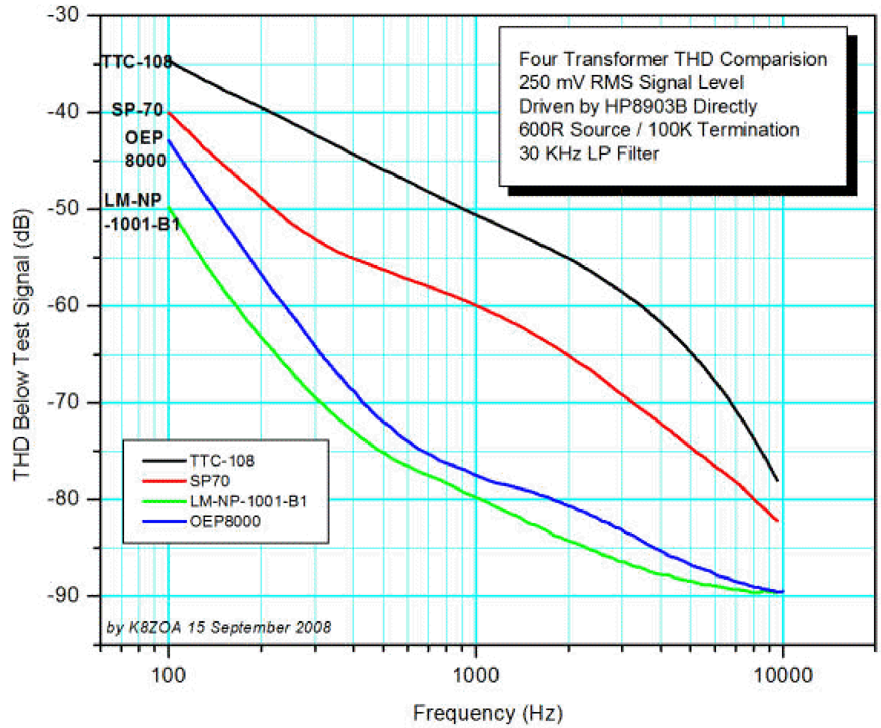
As they say around the race track, ï¿½there are horses for courses.ï¿½ Leaving aside the Western Electric repeat coils, and very expensive audio transformers such as those made by Jensen, http://www.jensen-transformers.com/, what are we to make of the Tamura, Triad, Walters and Bourns offerings tested?

Assuming THD is the primary selection criterion, then we must know the expected signal level. All three plots presented are taken with the distortion analyzerï¿½s audio source driving the transformer. As weï¿½ve seen, major improvements in THD are possible when a transformer is drive by a low impedance ï¿½zero ohmï¿½ source, so these comparison plots are worst case in that regard.

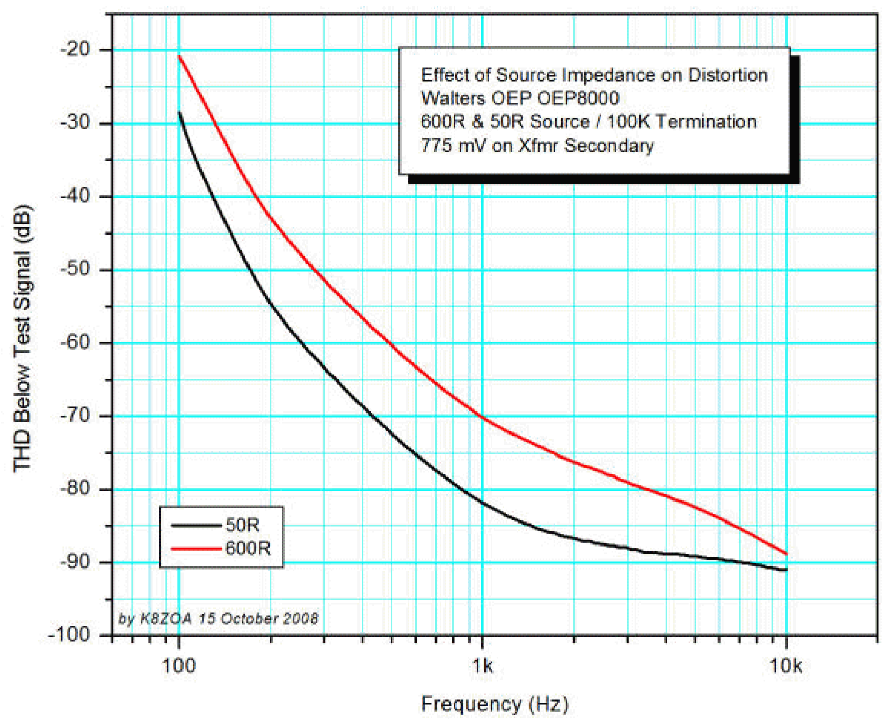
If we can be assured that the signal level will remain low, say 100 mV or less, Bournsï¿½ LM-NP-1001-B1 provides exceptionally low THD, as does the OEP8000. In fact, over 2000 Hz, the THD measurement is limited by the HP 8903B distortion analyzerï¿½s performance.



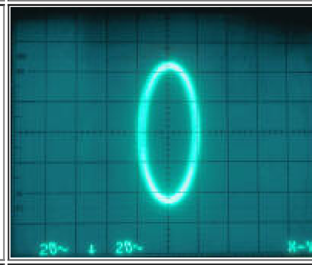
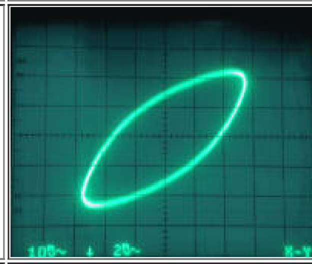
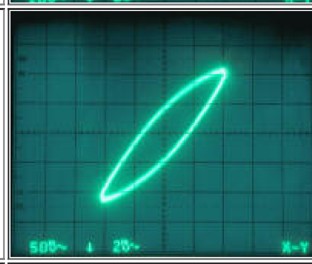
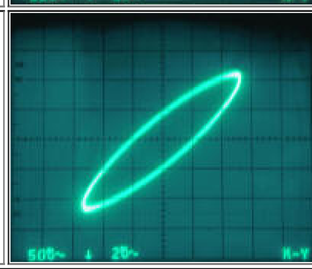
At 250 mV, the relative ranking of these four transformers remain unchanged, although we see the Bourns LM-NP-1001-B1 and Walters OEP8000 start to loose some of their comparative advantage over the other two transformers. At 100 Hz, all four transformers are closer together in THD, although the Bourns product is still 15 dB better than the TTC-108.



The picture is more mixed at 1000 mV RMS (+2.2 dBm), however. At lower frequencies, the OEP8000 is the best performer. However, above 400 Hz, the relative performance seen at lower voltage levels is restored, although the difference amongst the transformers is less than at lower voltage levels.



Itï¿½s also informative to look at the B-H curves for three transformers under the same test conditions and same oscilloscope gain settings. (I have not run B-H data for the OEP8000, as I acquired the sample parts after completing the B-H analysis.) The data is for 0 dBm (775 mV) applied at 150 Hz.

Transformer	B-H Image 775 mV (0 dBm)	Insertion Loss @ 150 Hz	THD @ 150 Hz / 1000 mV
Western Electric 119C		0.49 dB	-90.14 dB
Bourns LM-NP-1001-B1		1.12 dB	-39.9 dB
Triad SP-70		1.71 dB	-33.13
Tamura TTC-108		1.72 dB	-41.78

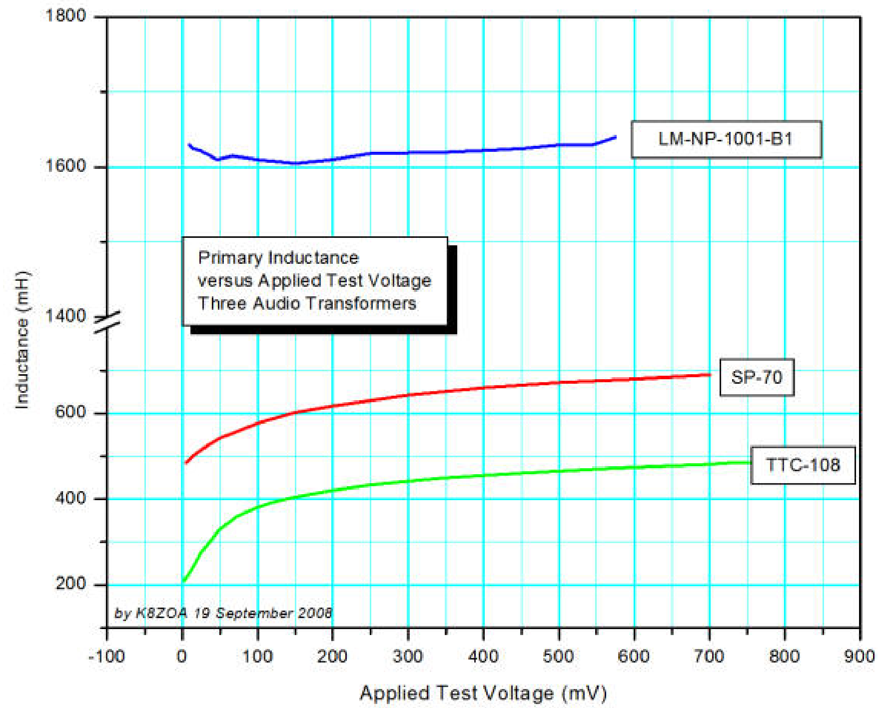
The area within the ellipse is proportional to hysteresis core loss and the larger the area, the greater the 150 Hz insertion loss. However, the series resistance of the primary and secondary windings have a much larger effect on insertion loss at this frequency and swamp the small differences in hysteresis loss.

Distortion should be proportional to the symmetry and linearity of the B-H curve, and the curves back this up to a large degree.

Primary Inductance Variation with Level

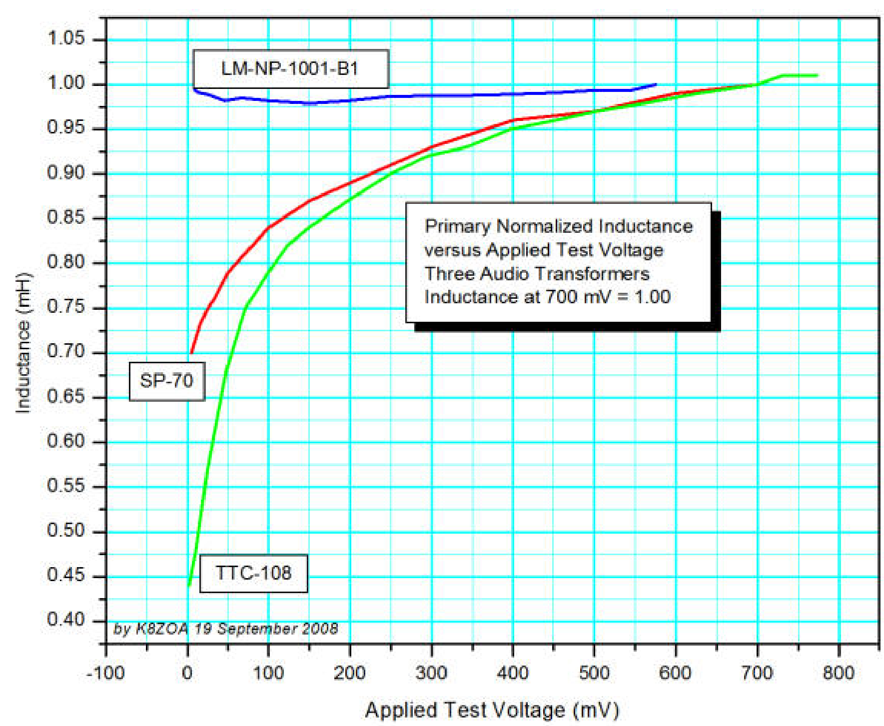
It occurred to me that a surrogate for distortion might be how the primary winding inductance varies with voltage. Accordingly, I measured the primary winding inductance for the Bourns, Triad and Tamura transformers over a range of test voltages. I used a General Radio GR-1650B RLC bridge, which has a variable oscillator drive that is convenient for this sort of test. The frequency used is 1 KHz.

The plot below shows the measured inductance versus test voltage for the three transformers. There's a clear difference between the Bourns and the Triad and Tamura transformers, with the Bourns showing essentially no change in inductance with applied voltage.



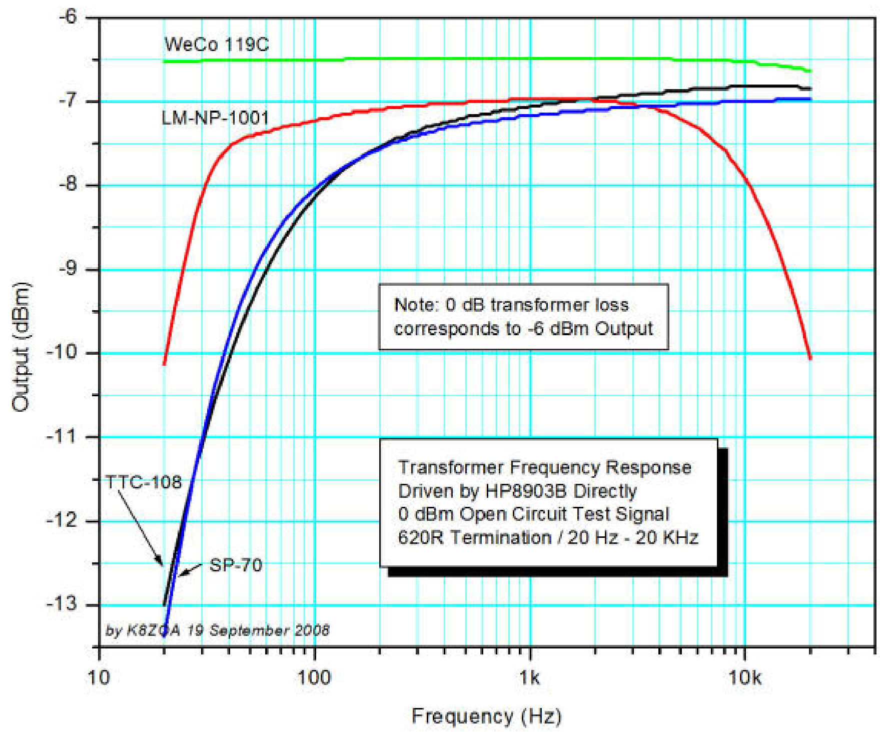
To make it easier to see the difference amongst the three transformers, I've plotted the normalized inductance, *i.e.,* with the inductance at 700 mV = 1.00

Based on the change of inductance with test voltage data, we would expect the Bourns transformer to have much lower THD at low voltage levels, followed by the SP-70, in turn followed by the TTC-108. In fact, this is exactly the order of THD performance for low voltage levels.



Frequency Response Compared

The plot below shows the frequency response of four transformers, driven with 600 ohms and terminated with 620 ohms. Leaving aside the 119C coil's nearly ruler flat response, the TTC-108 and SP-70 have almost identical frequency response characteristics. The Bourns LM-NP-1001-B1 has better low frequency response, but at the price of less high frequency response.

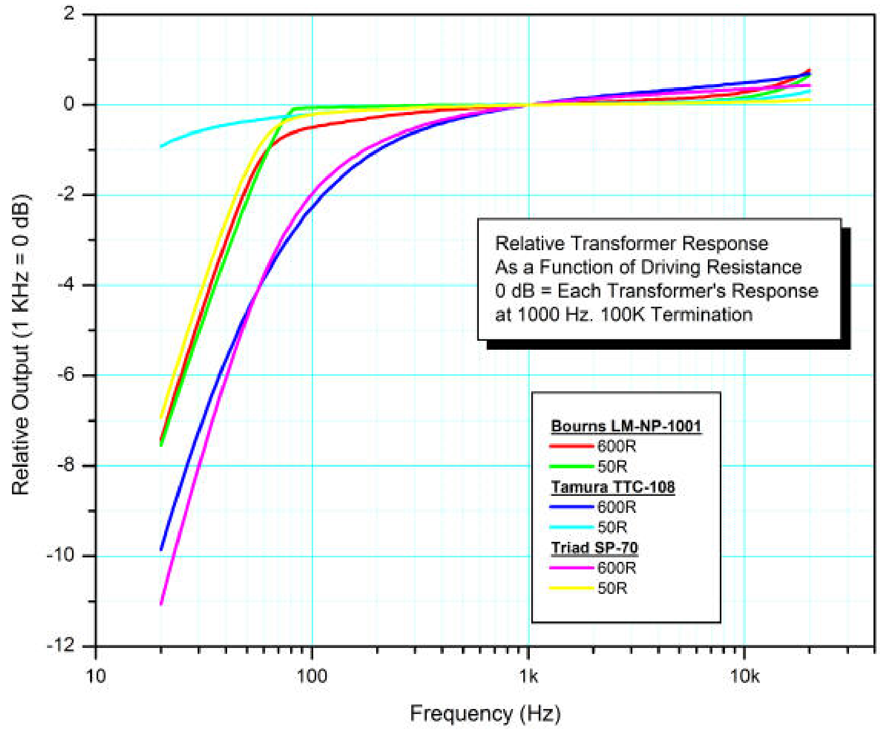


I've been asked to compare the frequency responses of the three inexpensive 600:600 transformers when driven by 600 ohms and 50 ohms, terminated into a 100K load.

Since the interesting part of this data is the relative performance of the transformers, I've normalized the data so that each transformer has 0.0 dB loss at 1000 Hz. Although the normalization washes out the insertion loss differences amongst the configurations, insertion loss is not a major consideration in this application.

The data shows considerable low end extension when driven with 50 ohms, save for the Bourns transformer, where the extension is more modest.

There's an anomaly with the Tamura TTC-108 data for 50 ohm drive. It's considerably better at low frequencies than when I measured it with different test equipment a couple weeks ago. I'll run it again and see why the discrepancy exists.



Stancor TTCP-2. TTCP-6 and TTCP-8

Paul Christensen, W9AC, sent me three Stancor telephone coupling transformers for analysis, models TTPC-2, -6 and -8. Because all three transformers are quite similar, I'll treat them together. These parts are quite similar in size to the TTC-108 I've covered above and are in the same price category and serve the same market; telephone coupling.

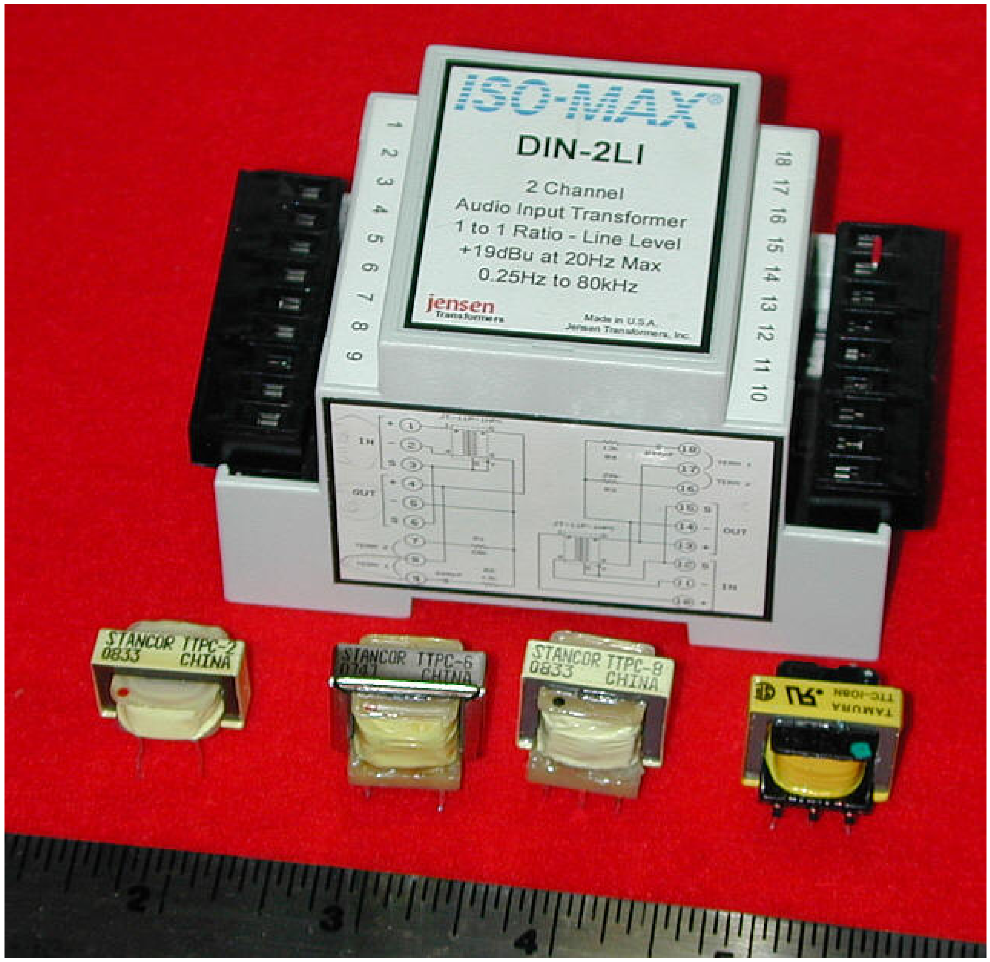
The differences amongst the three parts are related to center tap windings and, interestingly, the TTPC-6's ability to carry DC current. DC current rating is intriguing because it suggest a "beefier" core (also indicated by the TTPC-6 weighing twice as much as the -2 and -8 parts) and/or better core material with the prospect of improved low frequency response and lower distortion. Alas, the TTPC-6 isn't much different than the -2 and -8 parts and all three are close to the TTC-108.

The full specifications are available from Stancor at http://www.stancor.com/wrdstc/pdfs/Catalog_2006/Pg_019_20.pdf and I've extracted the key elements below.

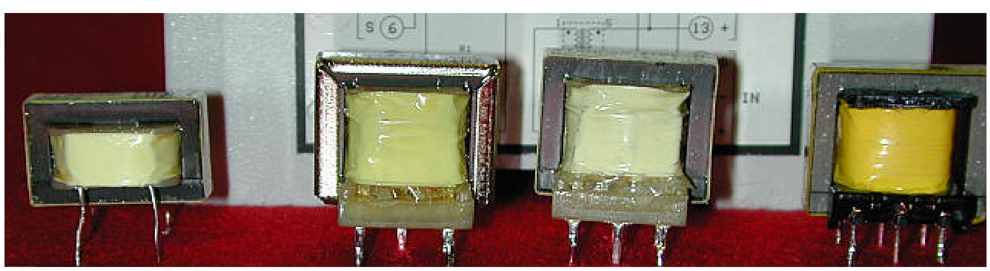
Telephone Coupling Transformer

Sec.	STANCOR PART NUMBER	Schematic Number	Style	Impedance Primary ± 15%	Impedance Secondary ± 10%	D.C. Curr. mA.	Insertion Losses db Max @1K Hz	Primary DCR
A	TTPC-2	1	B	600	600	0	1.2	46
B	TTPC-6	3	A	600	600 C.T.	90	1.8	71
	TTPC-8	2	A	600 C.T.	600 C.T.	0	1.2	36

The photo below shows the three Stancor transformers along with the Tamura TTC-108. At the rear is a DIN rail standard package with two Jensen audio isolation transformers, loaned to me for measurements by Ronald Wagner of Dynamic Research, Inc. Data for the DIN-2LI is presented later on this page. The DIN-2LI's enclosure size does not mean the transformers occupy the full space; the box is rather light.



It may not be clear from the angle of the photo, but the TTPC-2 is around half the height of the other two Stancor products and the TTC-108. The photograph below provides a better view of the relative height of the transformers. The TTPC-2's core is more rectangular than the other three transformers which are nearly square.



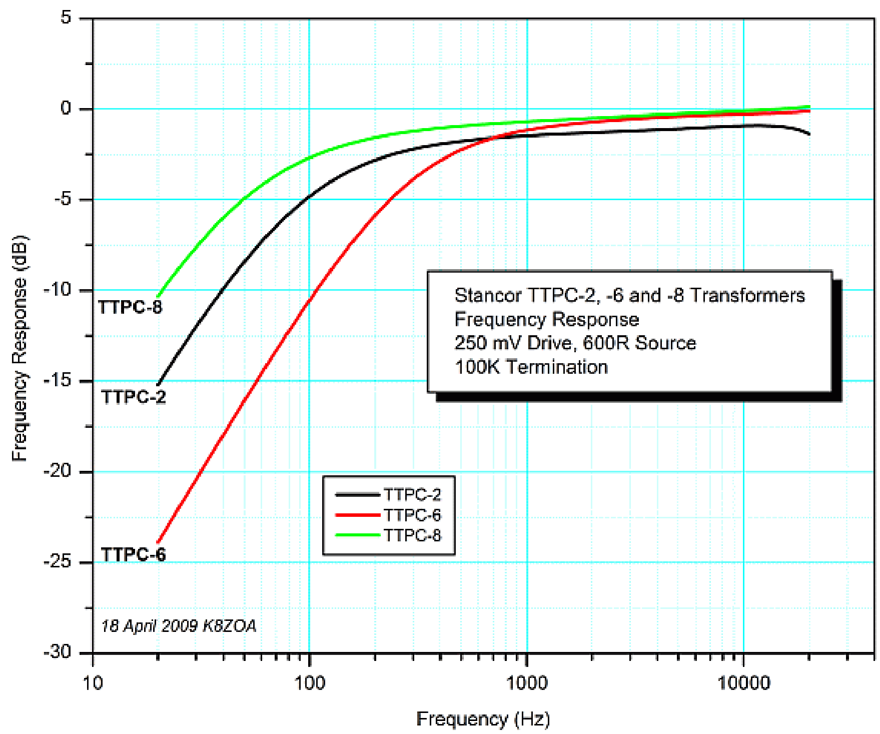
The figure below shows the frequency response of the three transformers over the range 20 Hz - 20 KHz. The data is taken with an HP8903B audio analyzer, driving the transformers with the internal audio generator set for 600 ohm impedance. The transformer is terminated into the 8903B's input section, representing a 100K impedance.

Interestingly, the TTPC-6 has the worst low frequency response, which can be understood as a side effect of it's DC current rating.

First, telephone coupling transformers are designed with a low frequency response target around 300 Hz, and at 300 Hz the TTPC-6 is down 3.8 dB, about 2 dB worse than the -2 and -8 devices. Still, the TTPC-6's low frequency response is more than acceptable for a telephone coupling transformer.

In order to accommodate DC current, the transformer designer must prevent the core from being driven into a non-linear range by the sum of the DC static magnetization field and the imposed AC signal. (Looking at the B-H curves, imagine the starting point being shifted. Clearly one polarity of the incoming AC waveform will drive the core closer to saturation whilst the opposite polarity will take the core away from saturation. Hence the output will exhibit a different response for each waveform half.)

The designer's bag of tricks include using a larger core, or different core material, or introducing an air gap in the core, or reducing the number of turns. Since the TTPC-6 is similar sized to the -2 and -8 parts, and since there seems to be no visible air gap, it is most likely that the TTPC-6's designer reduced the number of turns. This reduces the magnetizing inductance and also means the low frequency response will impaired.



I measured the four transformers (three Stancor and the TTC-108) primary inductance at 100 Hz and 1 KHz with a General Radio 1658 Digibridge. As the data shows, the TTPC-6 has considerably less inductance than either the -2 or -8 parts or, for that matter, the TTC-108. This suggests that the designer has solved the DC current dilemma by opting for fewer turns or by a core with lower permeability, or a combination of both. The DC resistance specification shows the TTPC-6 with nearly twice the DC resistance of the -2 and -8 transformers. If the -6 simply had fewer turns, then one would expect the DC resistance to be less than seen in the -2 or -8 transformers. This not being the case, the more logical answer is that the designer has opted for a different core material with lower permeability and higher resistance to saturation (or perhaps a gap core) and has added turns to bring the inductance back towards the minimum acceptable value to maintain a 300 Hz lower frequency -3 dB point.

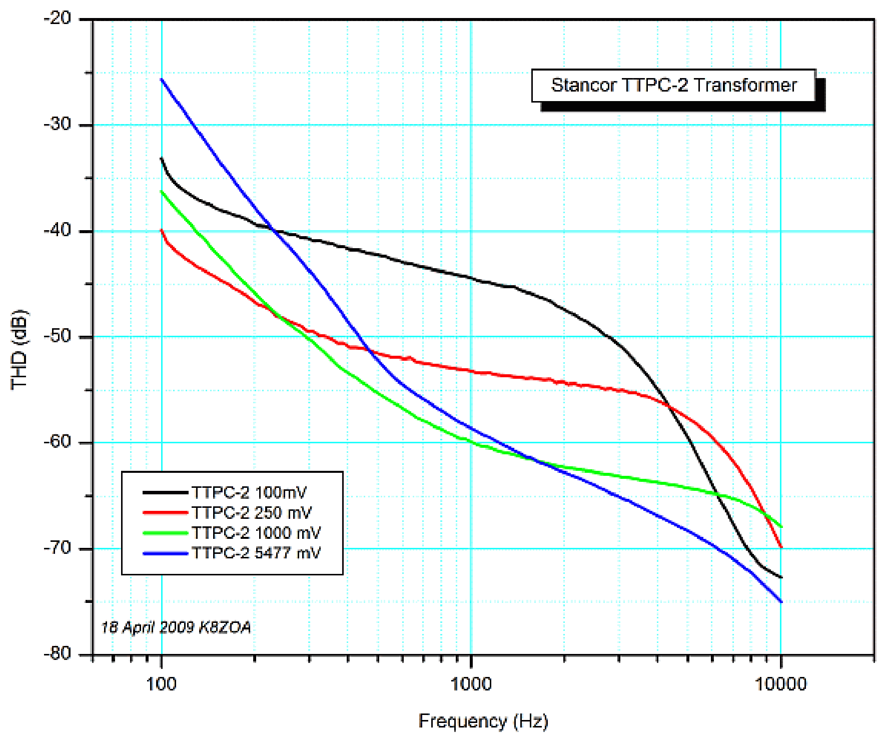
The difference in inductance between 100 Hz and 1000 Hz represents at least two factors. One is that the 1658 Digibridge applies different voltage levels at these two frequencies and incremental inductance depends on the applied test signal level. See Primary_Inductance_Variation_with_Level earlier on this page. Second, it's possible that the core material's permeability has some frequency dependency, although this is less likely to account for all the variation.

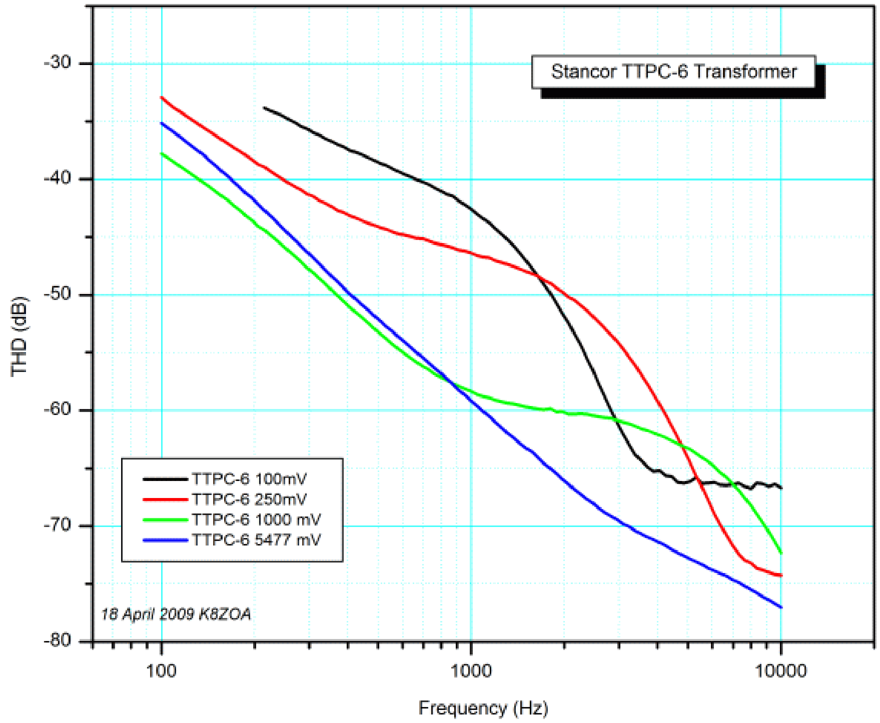
Transformer	100 Hz Inductance (H)	1 KHz Inductance (H)	Predicted 100 Hz Loss (dB)	Measured 100 Hz Loss (dB)
TTPC-2	0.80	0.38	-3.88	-4.7
TTPC-6	0.34	0.28	-9.50	-10.4
TTPC-8	1.27	0.44	-1.93	-2.6
TTC-108	0.97	0.46	-2.95	-3.08

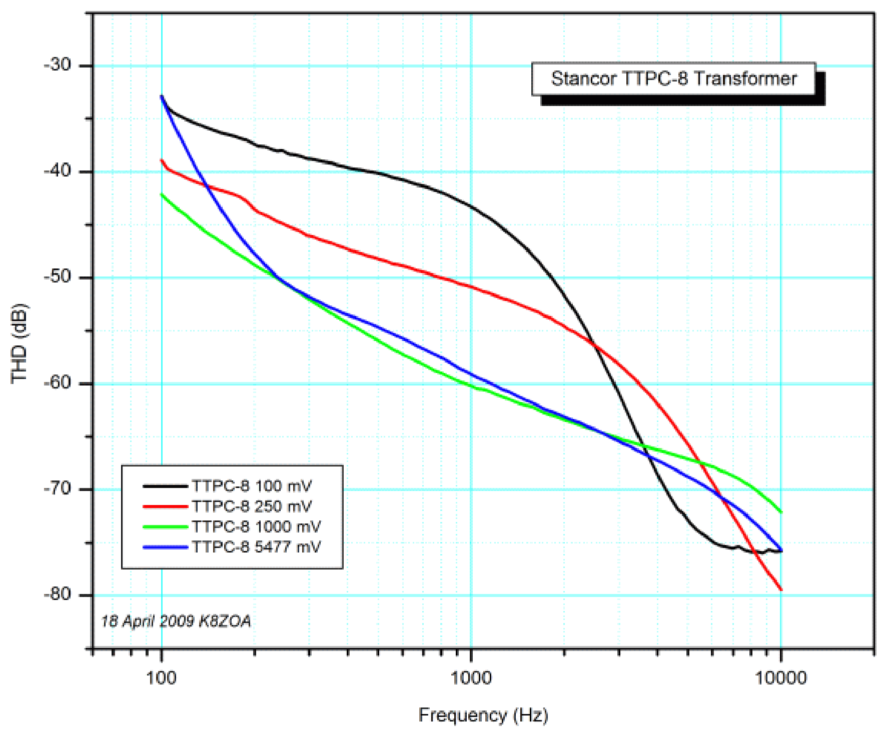
Incidentally, we can cross-check the measured 100 Hz inductance measurement against the observed 100 Hz insertion loss. With an open circuited secondary, the voltage developed is given by analyzing the transformer as a RL series network, with 600 ohms signal generator impedance and L being the measured value. (This ignores the winding series resistance, but this won't introduce too much error given the magnitude of the transformer resistance compared with the 600 ohm generator resistance. It also assumes the transformer turns ratio is 1.00:1.00.)

The simplistic prediction shows reasonably good agreement with the measured data If we enhance the model, for example, adding the TTPC-6's DC resistance, the predicted loss becomes 9.92 dB, bringing it considerably closer to the measured 10.4 db. When one considers the inductance versus drive level factor, we can't expect perfect agreement.

The next plot sequence shows the THD for the three Stancor transformers at the same drive levels in the earlier measurements. In all cases, the drive is applied with the 8903B source impedance set to 600 ohms and the transformer secondary unterminated, other than by the 100K input impedance of the 8903B's analyzer section.

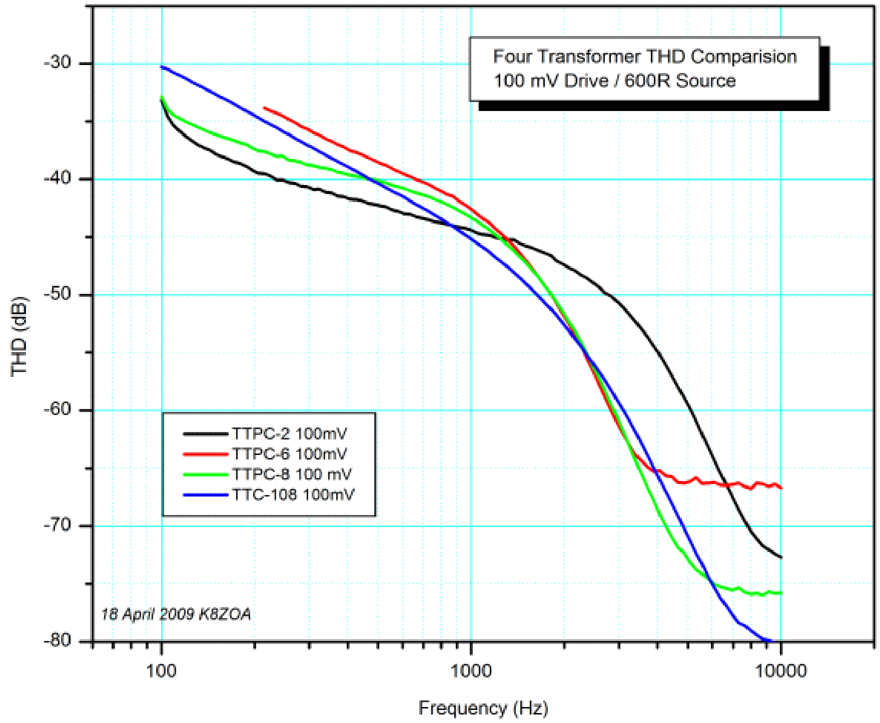






Of perhaps more interest than the individual plots is how these three Stancor products compare with the Tamura TTC-108 at an applied signal level typical of what one might find when used for a sound card input, as is the case in the K3's line output stage.

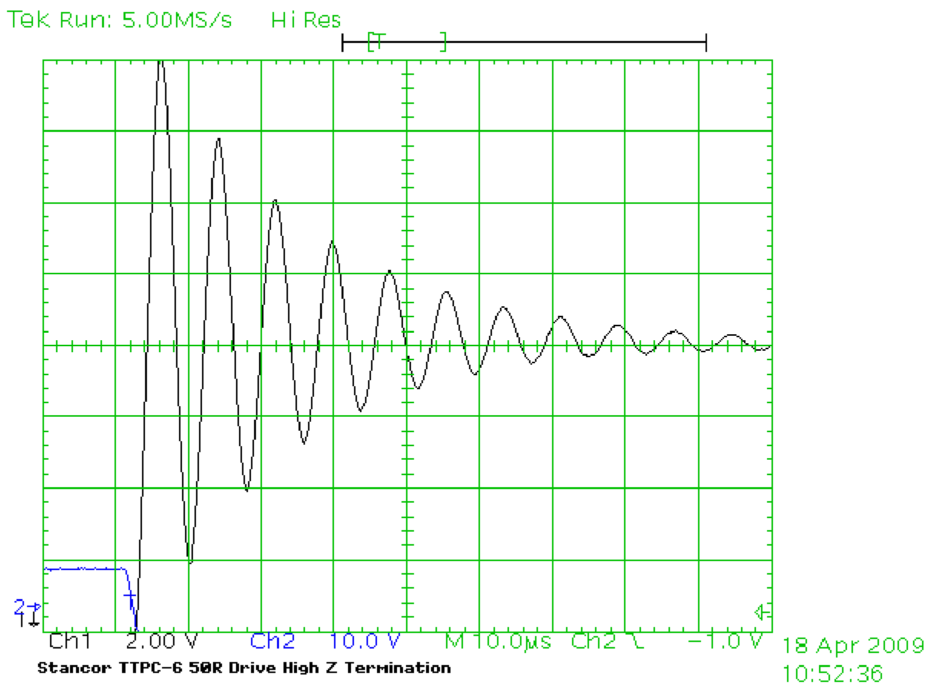
The plot shows the TTPC-6 is slightlyï¿½a matter of a dB or twoï¿½better than the TTC-108 up to 2 KHz. In fact, there's very little to chose from amongst these transformers. Above 1 KHz, the TTPC-2 is the best performer, but it's the worse below 1 KHz. Performance above 4 KHz is not material as the K3's bandwidth is limited to 4 KHz.

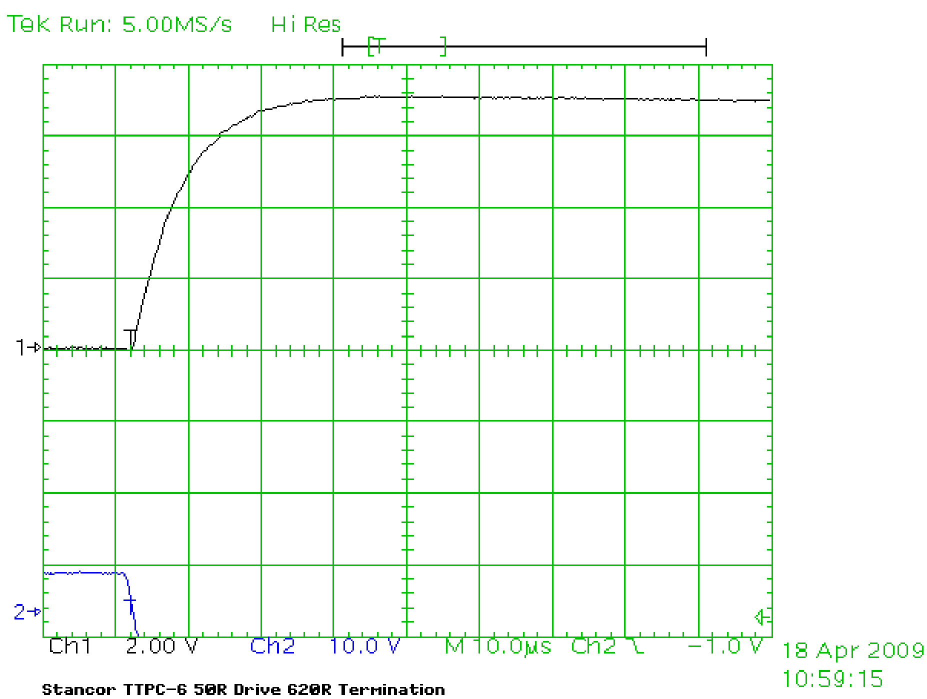


I've also run a square wave ringing test on the three Stancor transformers. Since the results are similar for all three, I'll just provide the TTPC-6 oscilloscope captures. As the image capture indicates, the first capture is with the transformer secondary terminated only by the oscilloscope 10X probe. The second terminates the secondary with 620 ohms. In both cases, the transformer is driven with a bipolar square wave with a 50 ohm source, an HP8904A multifunction synthesizer.

The data is generally similar to the other inexpensive transformers; unless terminated all exhibit a great deal of ringing. Of course, a microsecond rise/fall square wave is not a possible exciting signal when connected to a radio receiver, so this test may be of more academic than practical interest.

If ringing is of concern, the simple answer is to terminate the transformer with a suitable resistance, assuming other considerations permit.



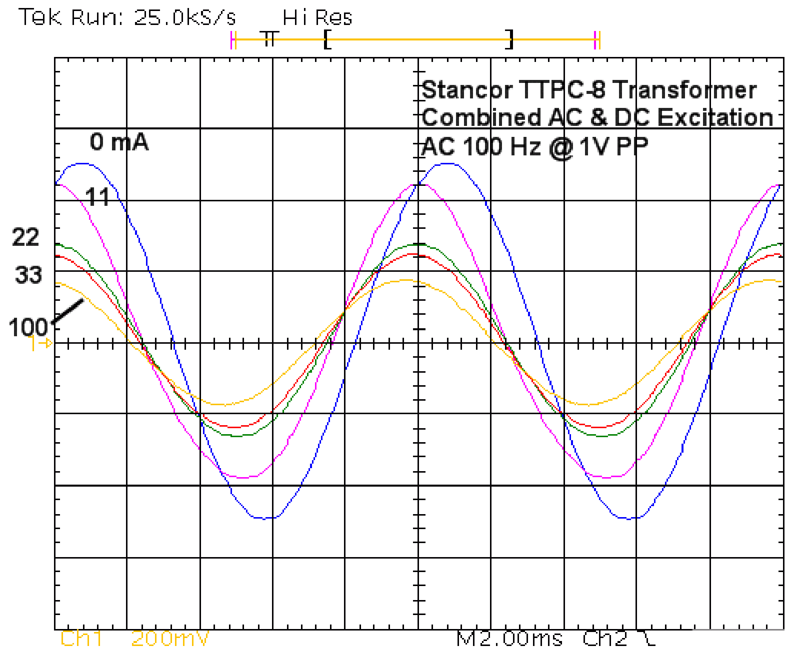


Effect of DC Bias on TTPC-6 and -8 Transformers

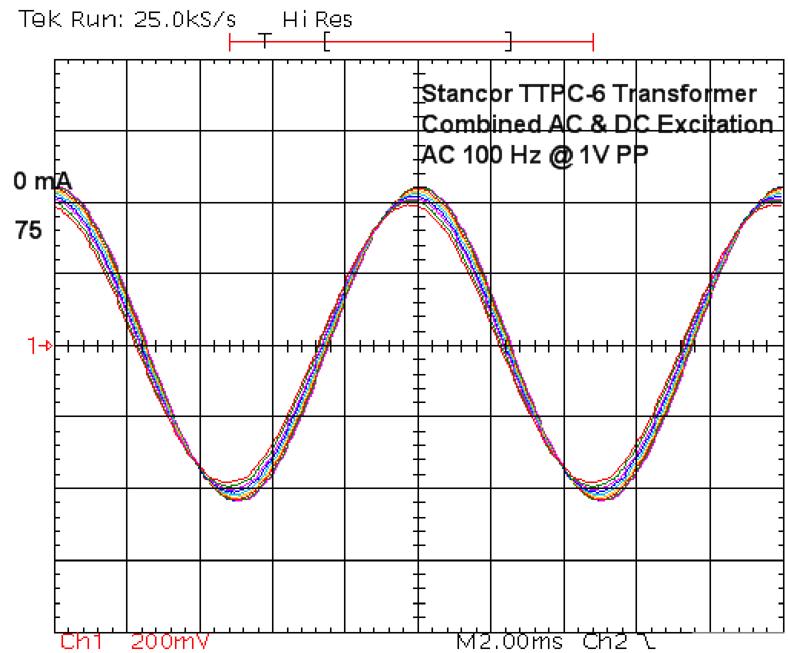
Is there a difference between the TTPC-6 and -8 transformers when DC current is applied to a winding, or does the 0 mA rating of the TTPC-8 mean anything? These are otherwise physically and electrically similar devices. To answer this question, I applied a 100 Hz 1 volt peak-to-peak sine wave with variable DC offset from an HP 8904A synthesized multifunction generator to one winding and looked at the resulting waveform on the transformer's other winding for a range of DC offset voltages and resulting current. I did not look at the effect of DC bias on THD.

The first image shows the effect of DC bias on a transformer not designed to accommodate DC current. As the DC bias increases, the output signal level drops some 10 dB between 0 mA DC current and 100 mA DC current. Most of the drop occurs at low current levels, with little change between 33 mA and 100 mA. There's also phase shift seen due to variation in the transformer's magnetizing inductance with current. (The 0 mA blue trace was not aligned with the center graticule line when I captured the data, so you'll have to mentally correct for my error.)

As a historical footnote, the effect of DC current in changing an iron core device's AC response is the principle behind magnetic amplifiers and saturable reactors. The DC bias shifts the operating point along the BH curve and thus varies the inductance and hence device impedance and gain.



In contrast, the TTPC-6 shows nearly negligible change in amplitude level as DC current is added to the winding. There's a very small but real phase shift also visible, a consequence of a small change in the transformer's magnetizing inductance with DC current. (The oscilloscope is triggered on a synchronization pulse from the HP 8904A synthesized source.)



So whatever the designer did to offset the harmful effects of DC on transformer response was successful in the TTPC-6.

Jensen DIN-2LI

Thanks to Ronald Wagner of Dynamic Research, Inc, I've been loaned a Jensen DIN-2LI dual isolation transformer to analyze. The 2LI's specifications are available at http://www.jensen-transformers.com/datashts/din2li.pdf and the performance specifications are eye popping. Note, for example, the THD figure; less than 0.001% (-100 dB) at 1 KHz and less than 0.04% (-68 dB) at 20 Hz

DIN - 2LI SPECIFICATIONS (all levels are input unless noted)

PARAMETER	CONDITIONS	MINIMUM	TYPICAL	MAXIMUM
Input impedance, Zi	1 kHz, +4 dBu, test circuit 1	13.0 kΩ	14.1 kΩ	15.0 kΩ
Voltage gain	1 kHz, +4 dBu, test circuit 1	−3.2 dB	−3.0 dB	−2.8 dB
Magnitude response, ref 1 kHz	20 Hz, +4 dBu, test circuit 1, Rs=600 Ω	−0.15 dB	−0.03 dB	±0.0 dB
	20 kHz, +4 dBu, test circuit 1, Rs=600 Ω	−0.35 dB	−0.20 dB	±0.0 dB
Deviation from linear phase (DLP)	20 Hz to 20 kHz, +4 dBu, test circuit 1, Rs=600 Ω		+1.4/−0°	±2.0°
Distortion (THD)	1 kHz, +4 dBu, test circuit 1, Rs=600 Ω		<0.001%	
	20 Hz, +4 dBu, test circuit 1, Rs=600 Ω		0.04%	0.10%
Maximum 20 Hz input level	1% THD, test circuit 1, Rs=600 Ω	+17 dBu	+19 dBu	

The 2LI has two independent transformers within the plastic enclosure. I believe these are JT-11P-1HPC transformers, with a different housing. http://www.jensen-transformers.com/datashts/11p1hpc.pdf

The -3 dB stated frequency response is from 0.25 Hz to 80 KHz, an incredibly impressive specification as well.

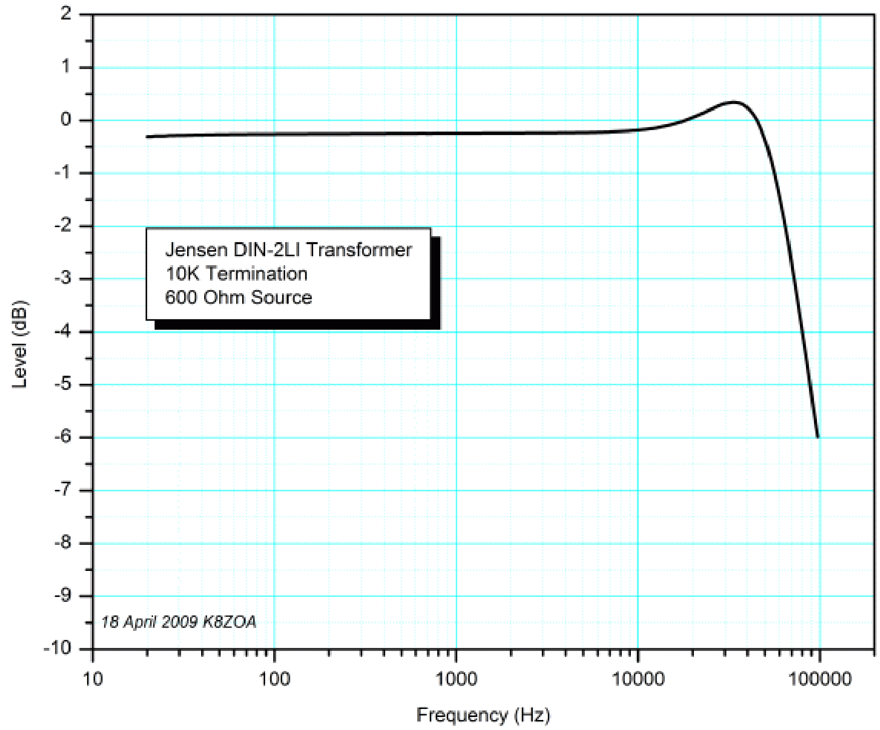
I should add that these performance levels are not without cost. The 2LI is roughly $200 each, or $100 per transformer. If you wish to purchase a single JT-110K-HPC without the fancy DIN enclosure, the price is $78. For comparison, the Stancor and Tamura parts are in the $3-4 range.

One additional point is that Jensen's transformers have a 30 dB magnetic shield. This is a very useful addition as I've noticed induced hum pickup in my K3's audio line transformers.

I also will add that these specifications are difficult or impossible for me to accurately measure in all respects, as they are better than the test equipment available to me. I'll identify where the measurements are test equipment limited.

The plot below shows the 2LI's frequency response from 20 Hz to 100 KHz taken with the HP 8903B, with the transformer terminated by the recommended 10K resistance. With other equipment, I could have looked at the response below 20 Hz to verify the 0.25 Hz -3 dB point, but did not do so.

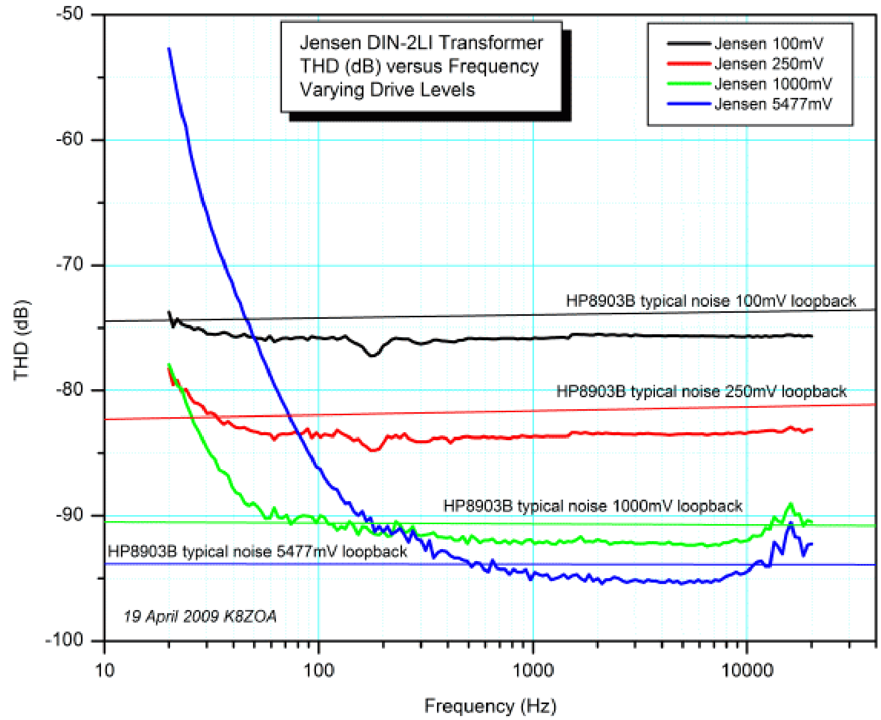
Quite an impressive response curve; ruler straight from 20 Hz to 10 KHz with a quarter dB or so rise up to 50 KHz and a measured -3 dB upper point of 75 KHz. That's a hair below the specification, but my test setup does not exactly duplicate the manufacturer's test protocol.



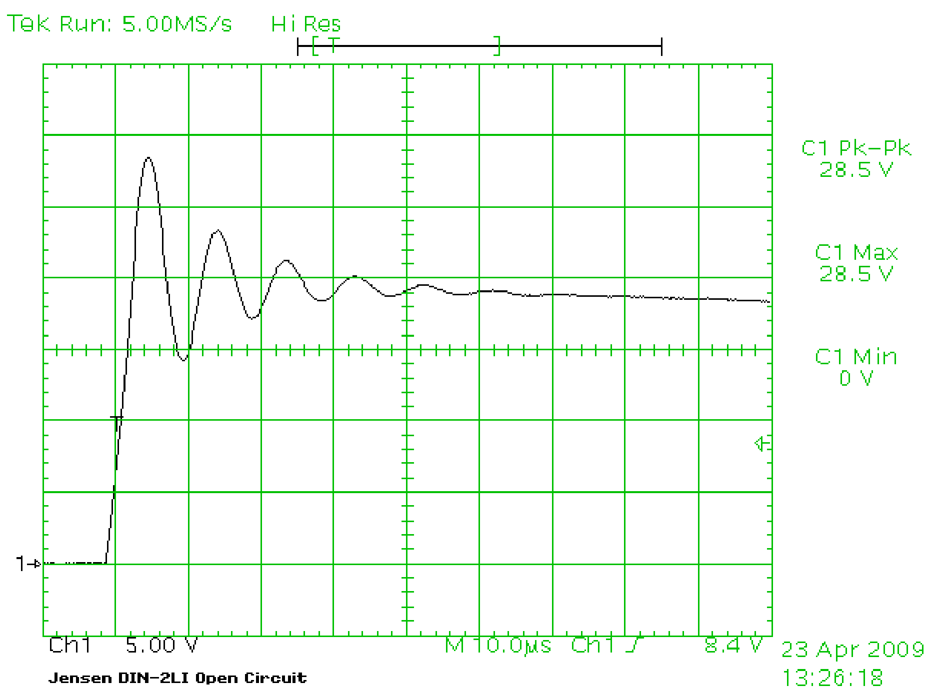
The figure below shows my measured THD data for the 2LI. I've added horizontal lines with the HP 8903B's noise floor for the particular drive level, taken by connecting the 8903B's output directly to the input (loopback). The Jensen data shows slightly less noise and distortion than the loopback test, which is due to the level and terminating impedance differences between the transformer in place and the loopback cables.

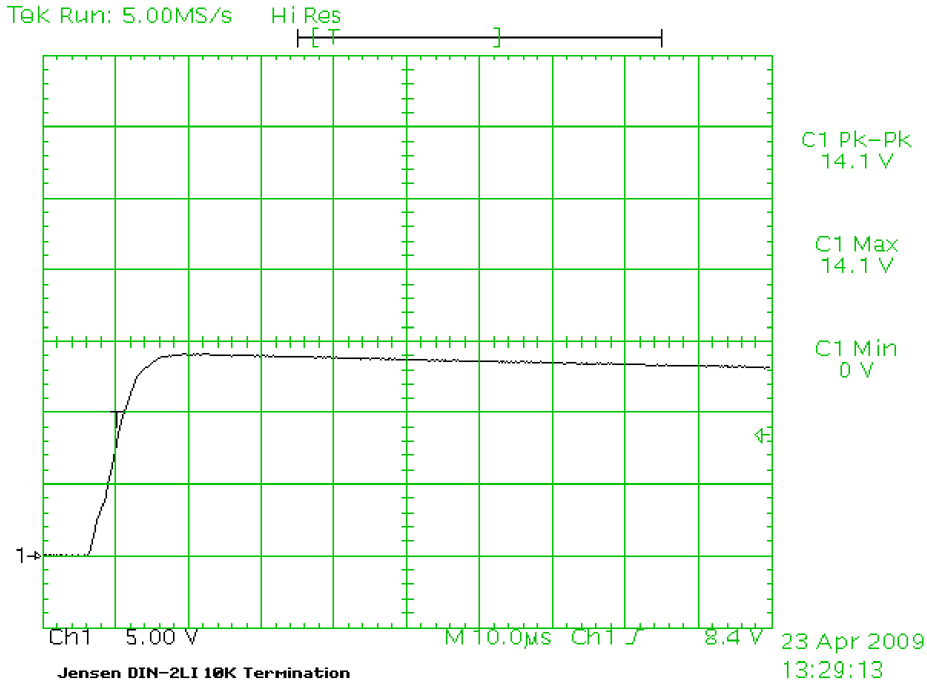
In essence, at 100 mV applied, all measured distortion is actually the noise floor of my 8903B. At 250 mV applied signal and stronger, there are areas of measured distortion above the noise floor for low frequencies.

With 5477 mV (RMS) applied, at 100 Hz I measured THD of -86 dB, or 0.005%. 5477 mV is +15 dBV, and at this combination of test frequency and signal level Jensen's data sheet shows 0.006% THD, interpolating between Jensen's +10 and +19 dBV data curves. This provides confidence that my data is correct, at least where the transformer's parameters are within the limits of my test gear.



I also looked at the DIN-2LI's response to a square wave, with the results shown below. Even un-terminated, the 2LI's response exhibits much less ringing than the other transformers, a characteristic it shares with the Western Electric 119C repeat coil. This square wave response is a function of the transformer's inductance, stray capacitance and resistance. The higher resistance seen in the 2LI means greater damping of the induced ringing.





B-H Curve Analysis of Stancor, Jensen and Western Electric Transformers

I wondered how the Jensen transformer's performance would show up in its B-H curve, and how it compares with my previous best performing transformer, the Western Electric 119C. I revised the B-H circuit used earlier to reflect direct current measurement via a Tektronix TCP-202 current probe, but the concept is unchanged. The horizontal axis is proportional to the transformer's current and the vertical axis is proportional to the magnetic flux, as sensed by integrating the voltage with a simple RC integrator. The tests are done at 150 Hz and the data captured with a Tektronix TDS-430 digital oscilloscope. The exciting signal is obtained from an HP 8904A synthesized multifunction generator driving a Kepco BOP 100-1M bipolar power supply / amplifier. This permits applying up to 200V PP across the transformer winding, with a maximum current of 1A, although the actual current levels are much lower than the maximum permitted by the power supply / amplifier limit.

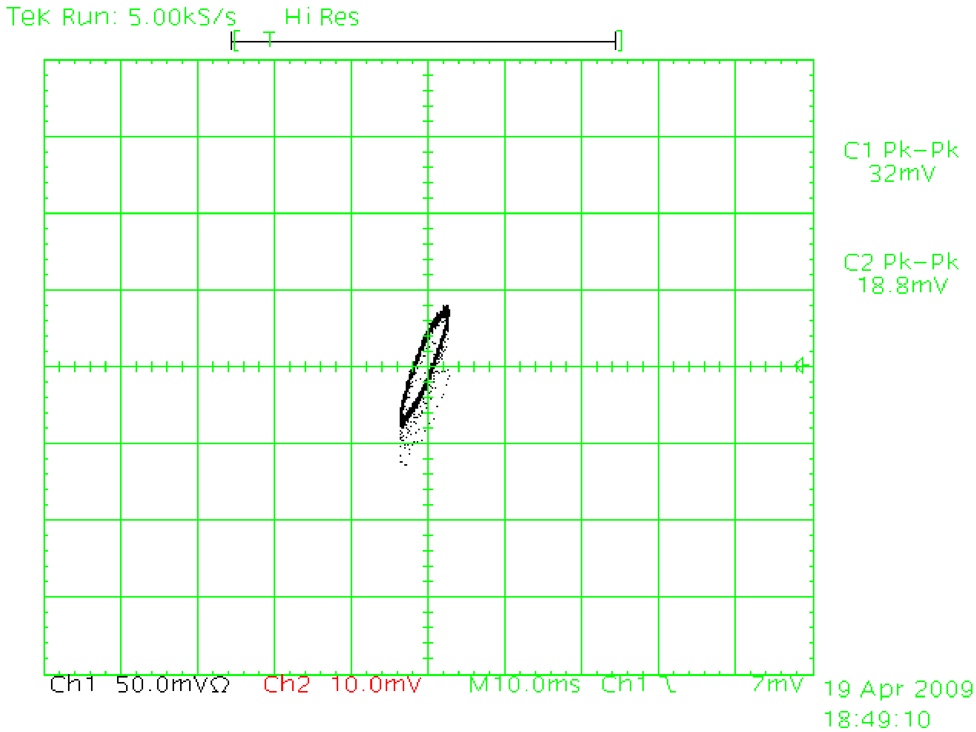
The horizontal axis (Ch 1) is in millampere x 5, so the scale 50mVΩ corresponds to 10 mA per division. (The factor of 5 exists because I wrapped five turns of wire around the TCP-202's pickup jaw to increase its sensitivity.) Channel 2 is the integrator output voltage.

TTC-108 B-H

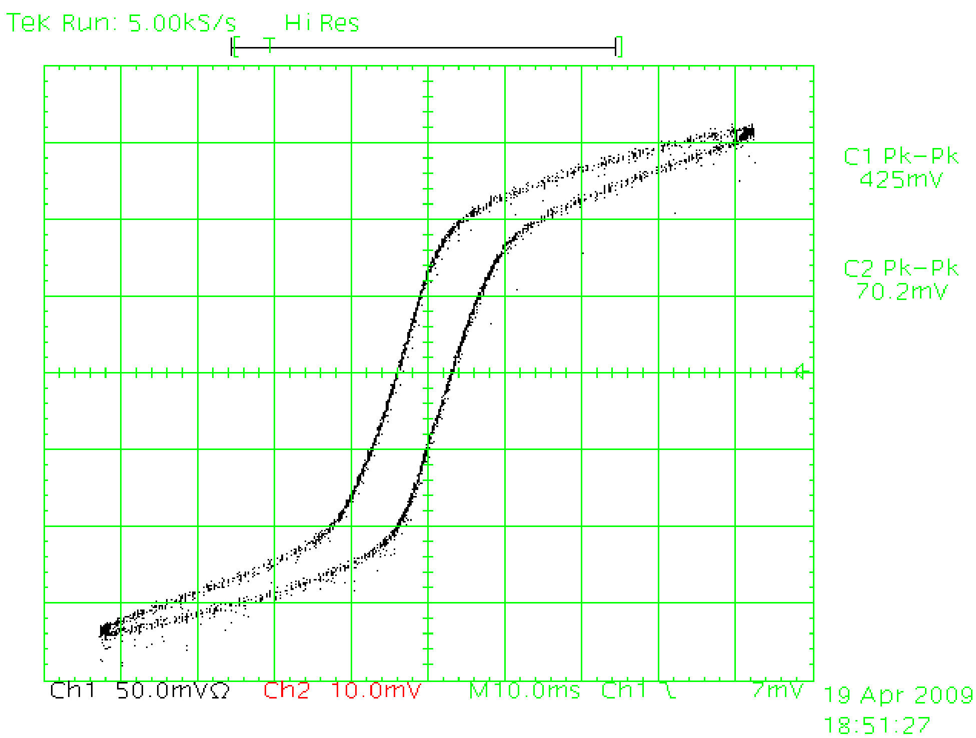
As a point of comparison, I also ran the Tamura TTC-108 transformer at 10 and 40 volts PP excitation, with the results illustrated below.

At 10 volts, the B-H curve is elliptical with no signs of saturation; at 40 volts, the TTC-108 exhibits major saturation, with the break point occurring with less than 10 mA current.

10V PP Excitation



40V PP Excitation

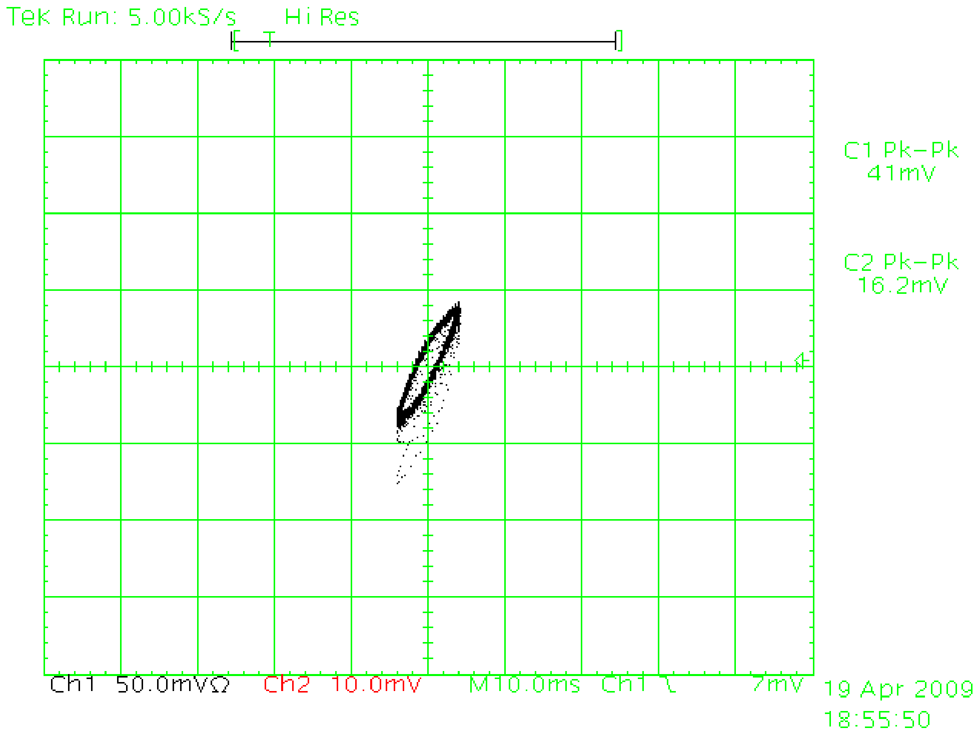


TTPC-2 B-H

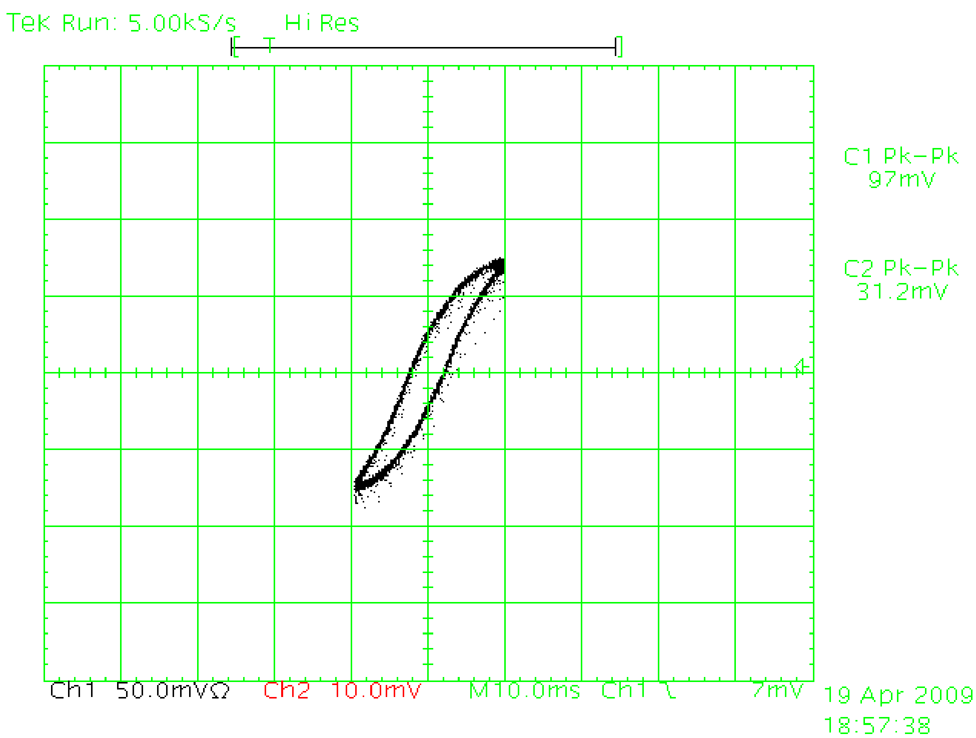
At 10V PP excitation, the TTC-108 and TTPC-2 B-H ellipses are quite similar, and the more traditional B-H waveform appears in the 20V PP capture. At 30V PP, the TTPC-2 shows gross saturation, which becomes even worse at 40V. (Note the change in scale in the last plot.)

Comparing the TTC-108 and TTPC-2 at 40V, it appears that the the TTPC-2 is driven further into saturation and that the linear region of the B-H curve is smaller.

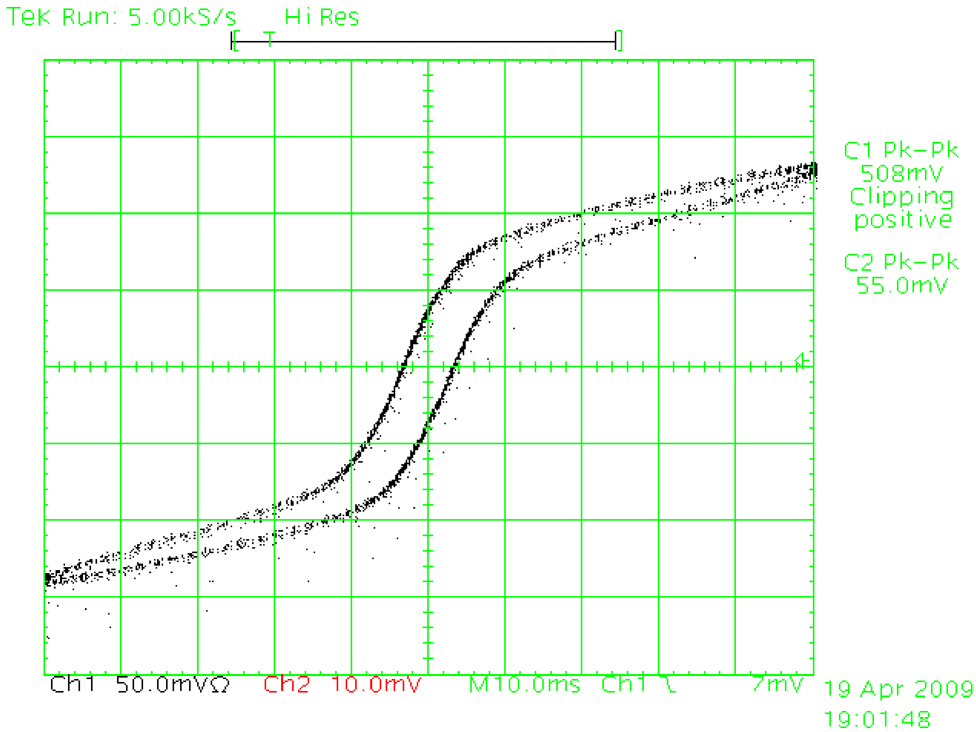
10V PP Excitation



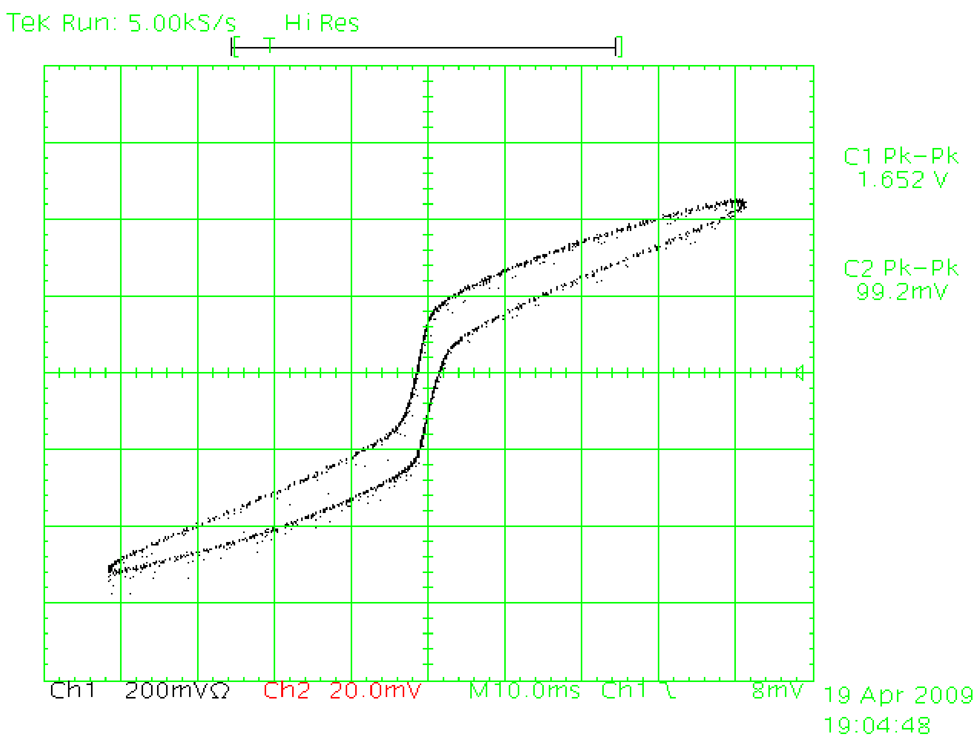
20V PP Excitation



30V PP Excitation



40V PP Excitation

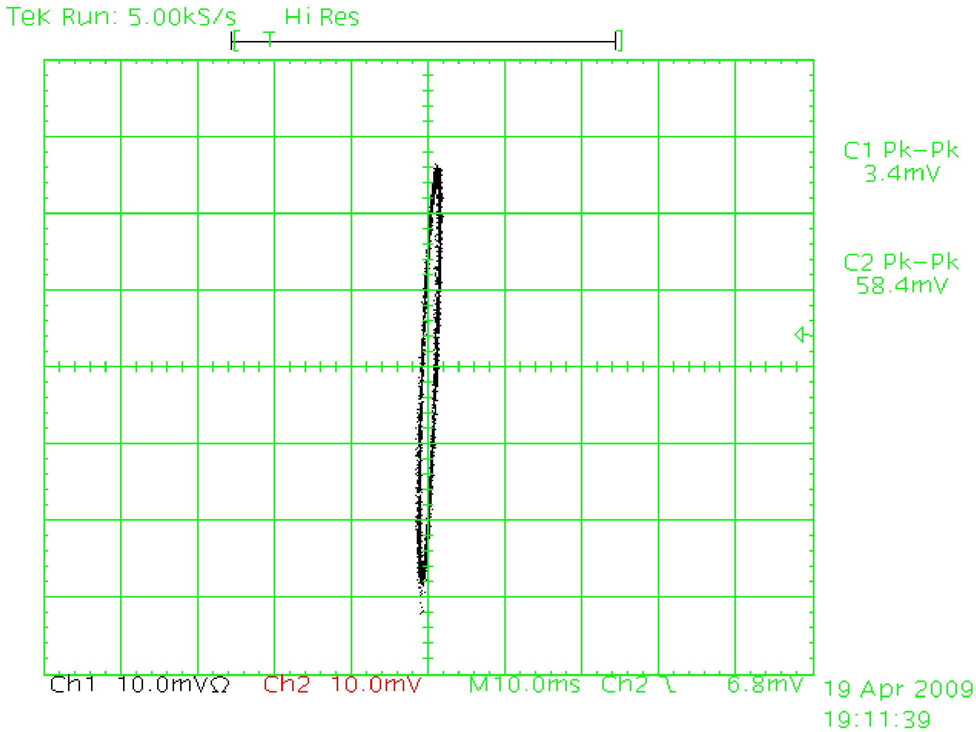


Western Electric 119C Repeat Coil

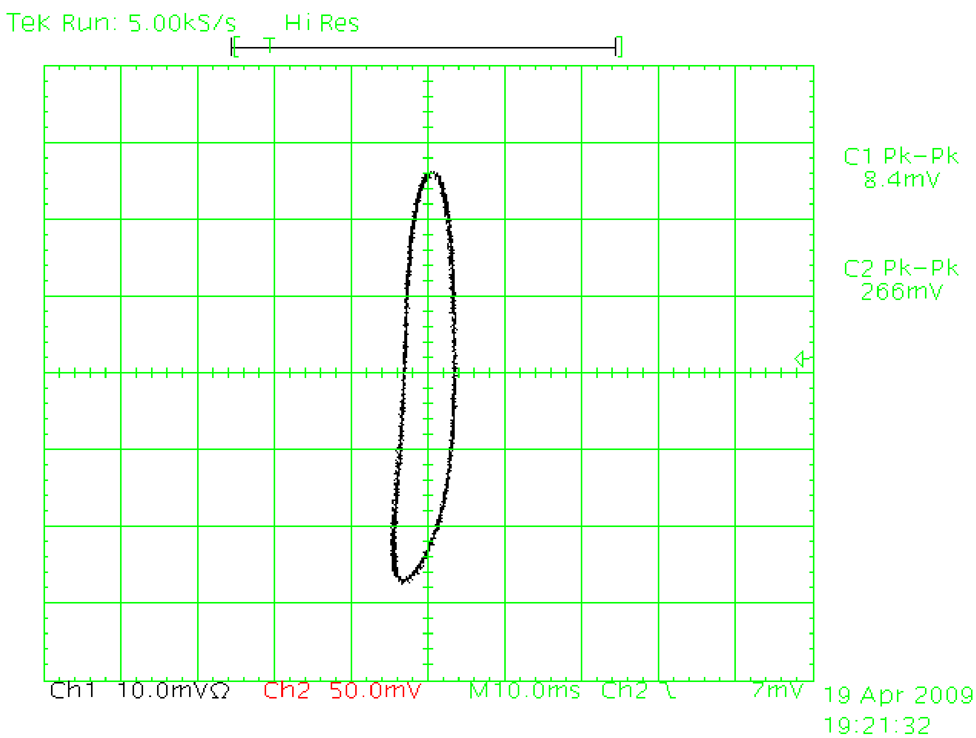
With 40V PP excitation, the 119C repeat coil is a small ellipse. Note that I've increased the horizontal axis gain to 2 mA/division in both 119C plots below. The area within the B-H curve represents hysteresis loss and it's gratifyingly small compared with either the TTC-108 or the TTPC-2 parts. There's no hint of saturation in the B-H curve.

Even with 200V PP appliedï¿½the maximum output of the BOP 100-1M amplifierï¿½the 119C's B-H curve shows no signs of saturation. The ellipse is certainly not symmetrical, but it's not saturated.

40V PP Excitation



200V PP Excitation

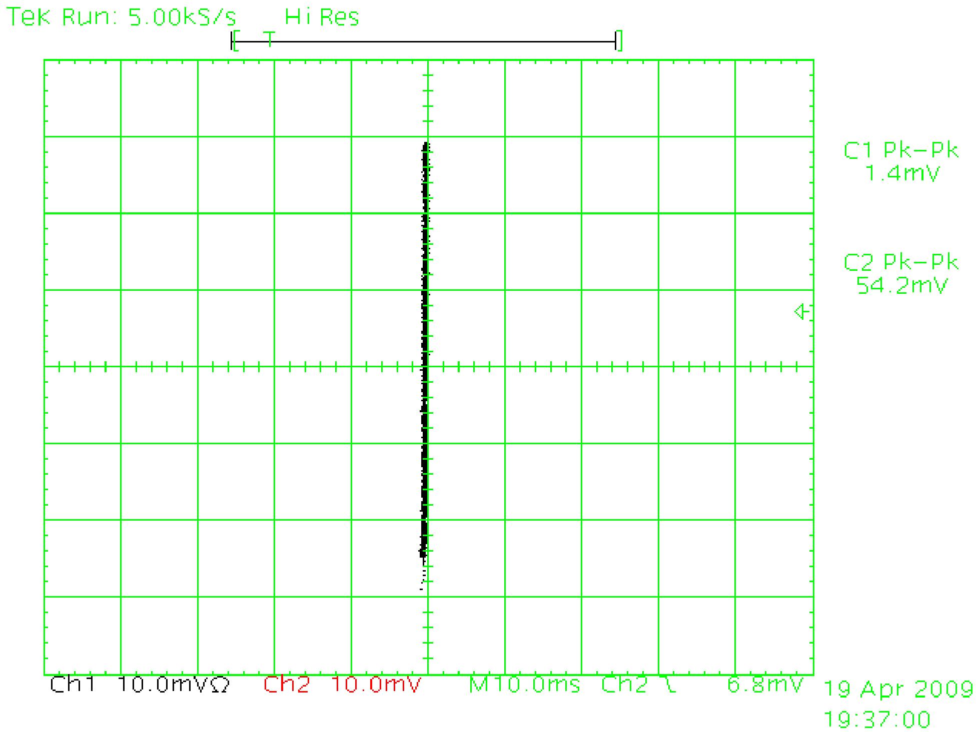


Jensen DIN-2LI B-H

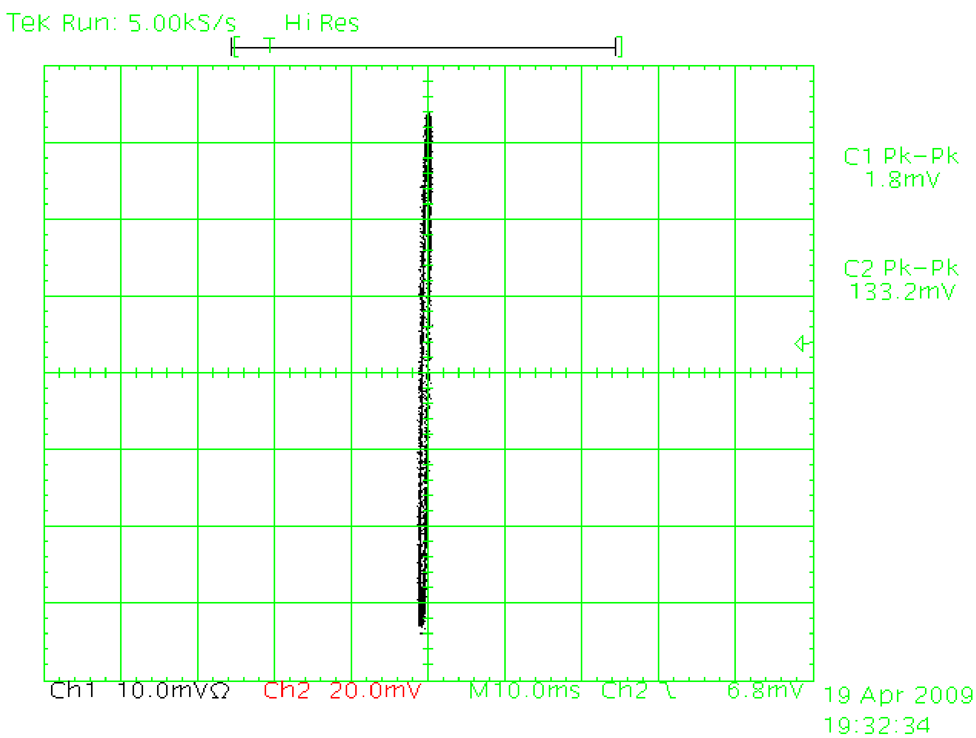
As good as the 119C coil isï¿½and it's good indeedï¿½Jensen's 2LI transformer is significantly better. Indeed, the B-H curve is not resolvable beyond what appears to be a single line with 40V PP excitation. Even at 100V PP excitation, the B-H curve is just starting to open.

At 150V, however, we see clear signs of saturation. Indeed, the B-H curve looks almost like of a square loop material, linear to the break and then nearly horizontal. More of this behavior is visible at 175 and 200V PP excitation.

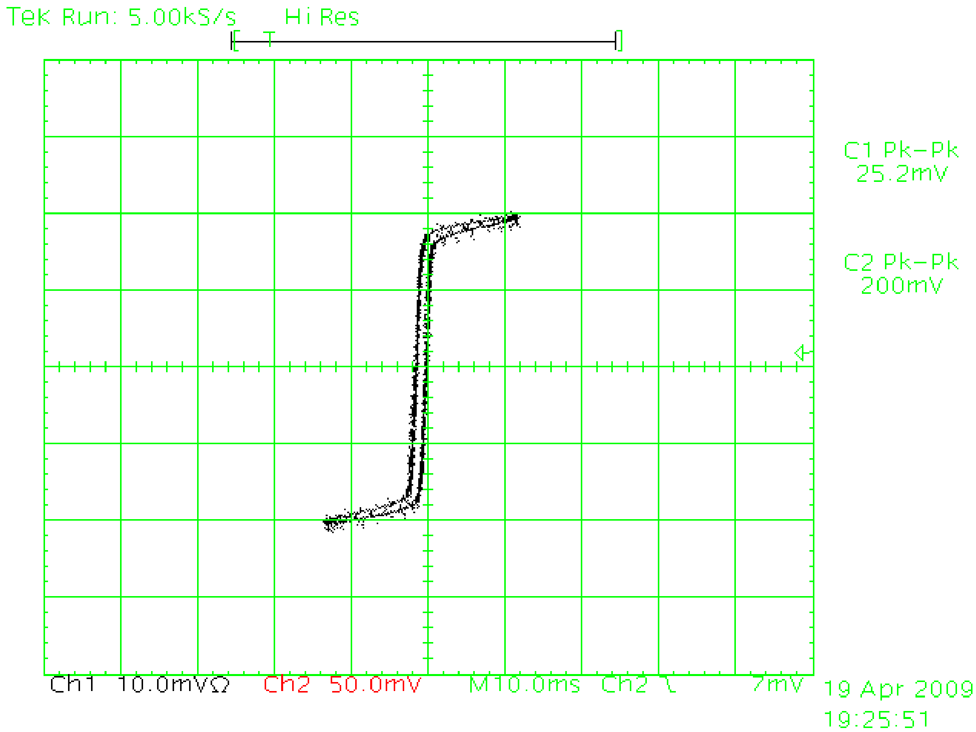
40V PP Excitation



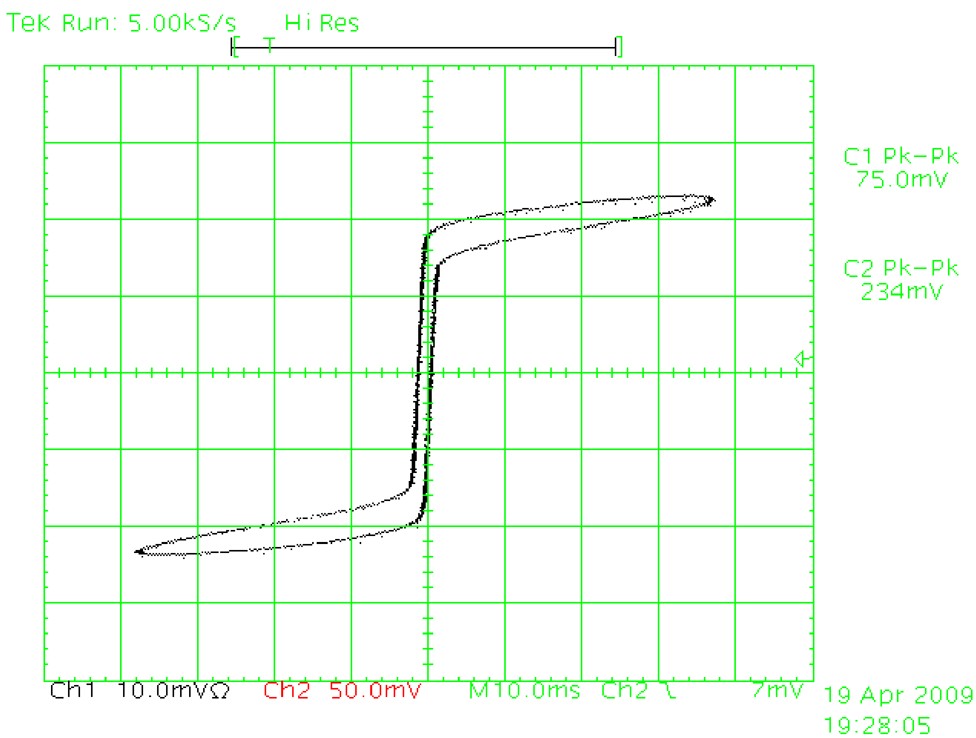
100V PP Excitation



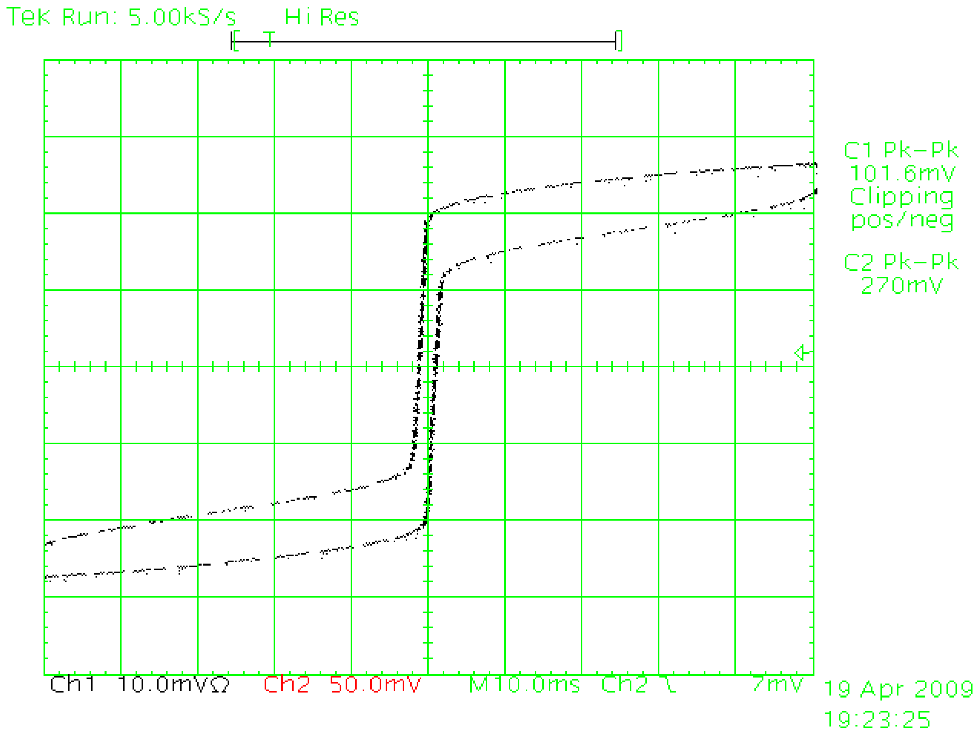
150V PP Excitation



175V PP Excitation



200V PP Excitation

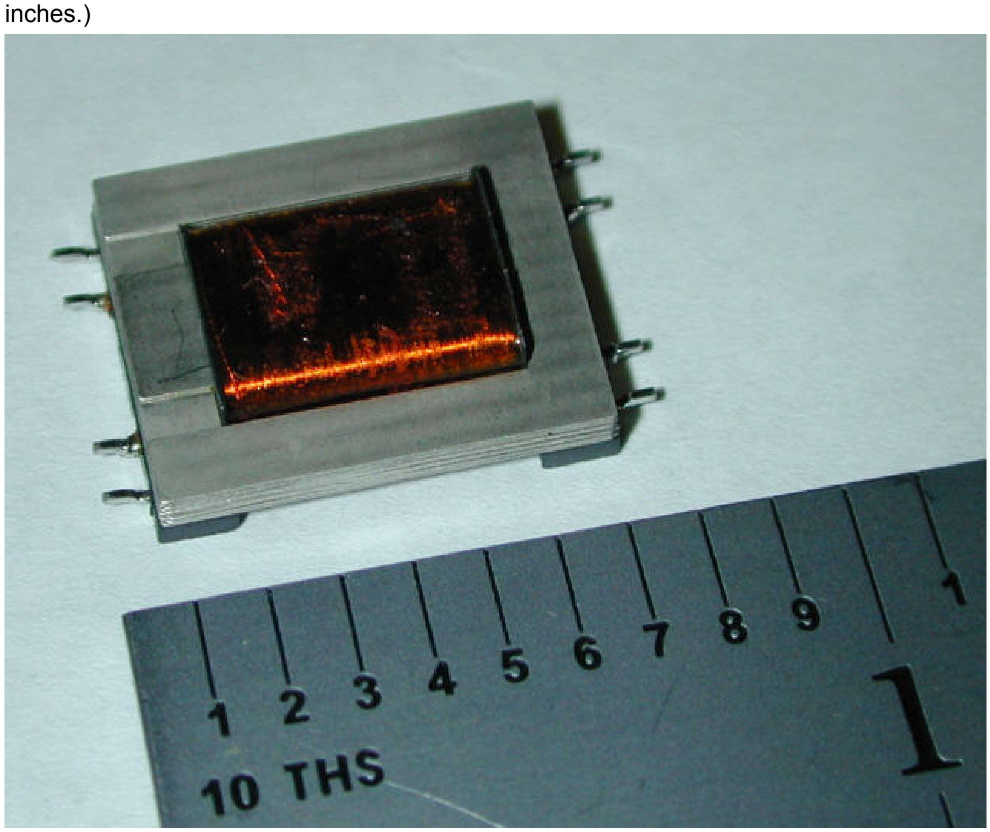


BG Incorporated KS Transformer

Joop, PE1CQP, sent several BG Industries model "KS" transformers for evaluation. These are data coupling transformers for telephone modems up to 56K BPS. The particular transformer is available in several variants relating to pin placement and height, but with identical electrical specifications.

The "KS" designation indicates, by the way, indicates the part was designed for and supplied to Western Electric for Bell System equipment. (These parts are identified with a multi-digit KS-xxxx sequence, sometimes followed by a Lx suffix for variants.)

This is a small surface mount transformer, so thin, in fact, that the laminations are easily counted. The ruler in the photograph is in inches and tenths. (The height is less than 0.200 inches.)



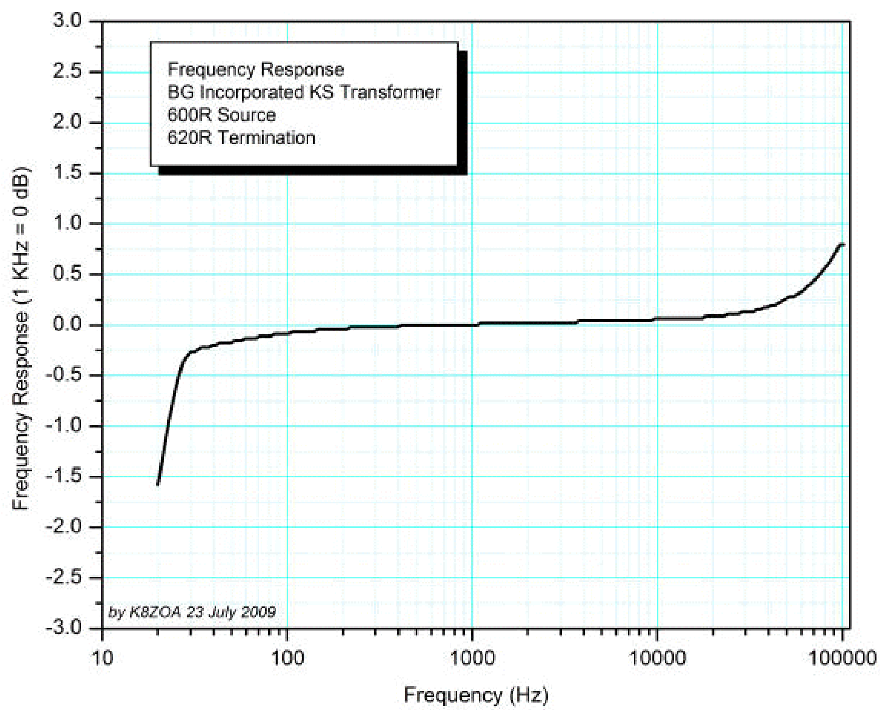
The relevant specifications are:

Impedance Source/Load	600/280 Ohms
DC Resistance PRI/SEC	160/190 Ohms
Insertion Loss	3.5-3.7 dB
Frequency Response	±0.2 dB 50Hz-50KHz, -10 dBm OUTPUT
Harmonic Distortion	-73 dB, 150 Hz, 280 Ohm Source, -3 dBm across 600 ohm load
Max Output Power	+9 dBm
Turns Ratio	1:1 ±2%

I don't understand how a transformer with a 1:1 winding ratio matches 600 to 280 ohms, but perhaps it's related to an intentional mismatch for a reason unknown to me.

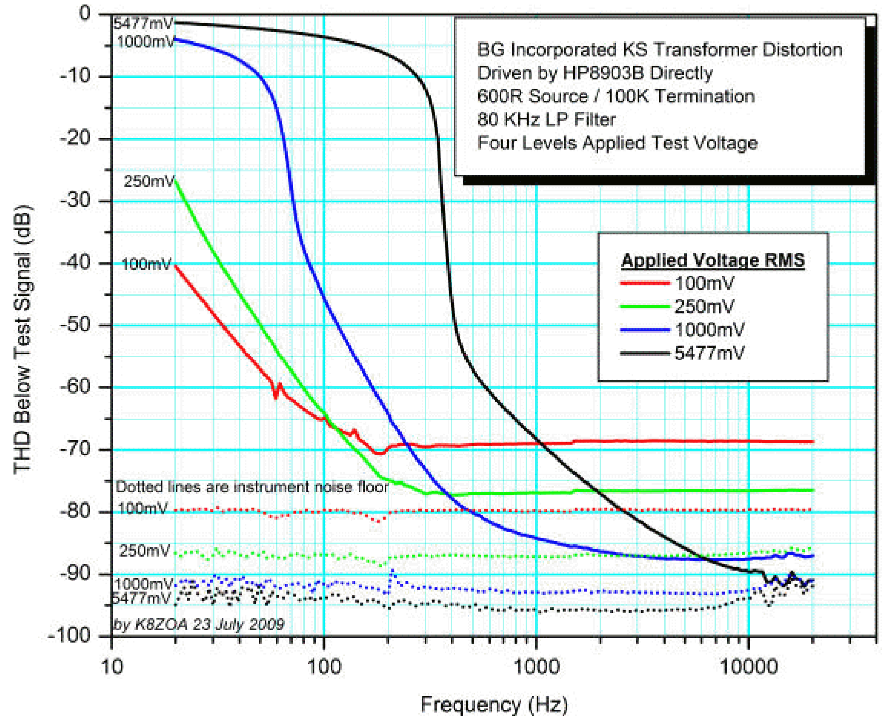
BG Inc. KS Frequency Response

The specifications sheet rates the KS transformer's frequency response as ±0.2 dB, 50 Hz - 50 KHz, and in fact it's remarkably flat over the frequency range 20 Hz - 100 KHz, as reflected below. Over this frequency range, the level response varies from -1.5 dB to +0.8 dB, and over the more usable range 50 Hz - 50 KHz, the level varies less than 0.2 dB. While not in the same league as Jensen's offering, it's much better than any of the inexpensive transformers reviewed on this page, particularly considering the data reflects 600 ohm drive.



BG Inc. KS THD

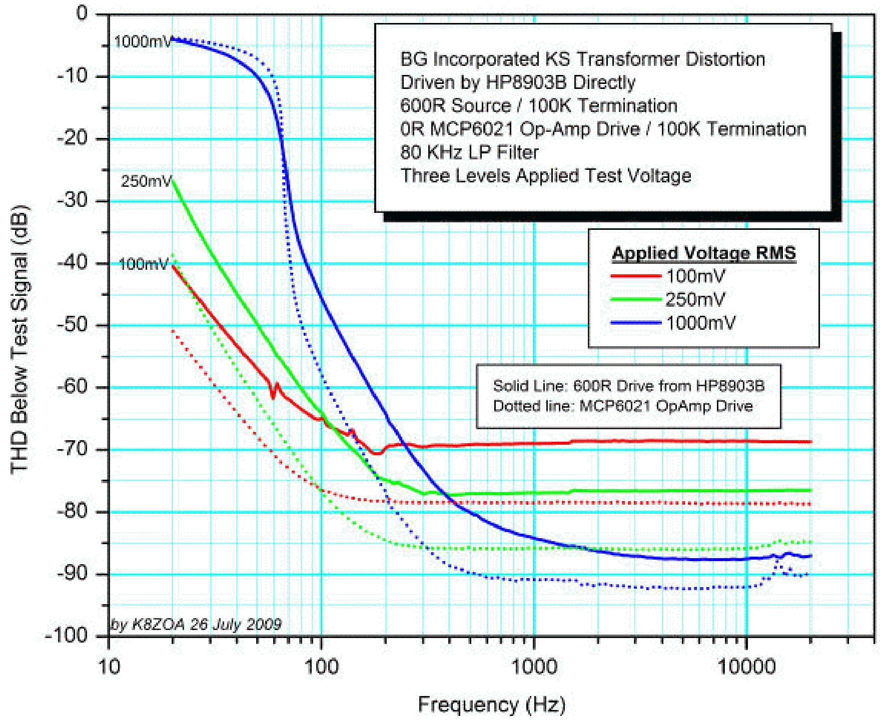
The KS transformer is not a bad performer in terms of THD, at least so long as some attention is paid to signal levels. Note that the data presented is for a wider frequency range (20 Hz - 20 KHz) than in some earlier plots.



KS Transformer Driven by Op-Amp "Zero ohms" Source

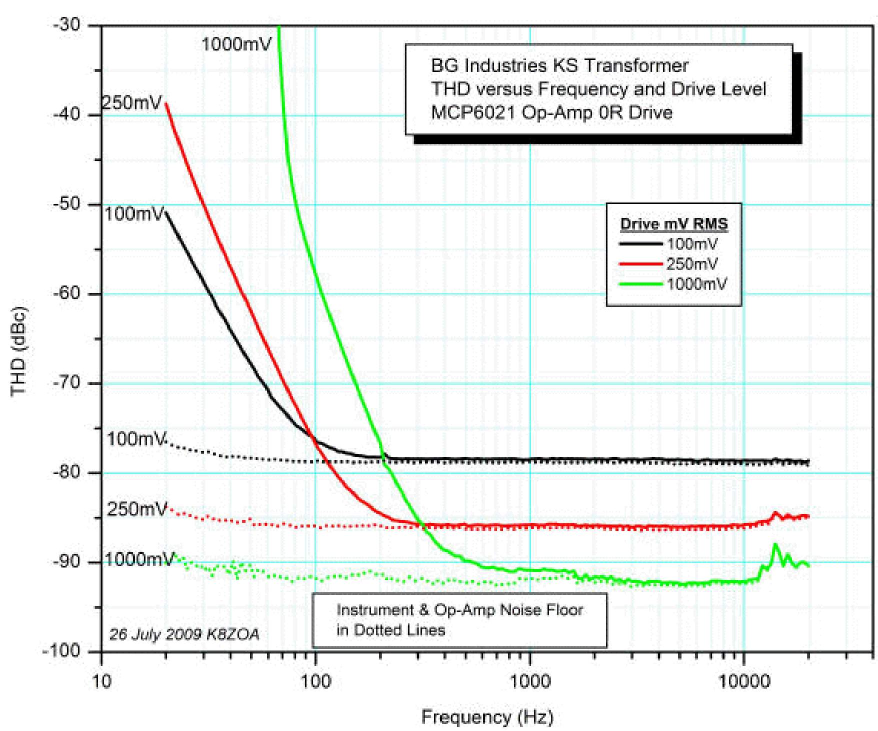
I've been asked to comment on the KS transformer performance when driven by a "zero ohms" source such as an op-amp with negative feedback. I used the MCP-6021 voltage follower circuit discussed earlier on this page, modified for better low frequency performance by increased input blocking capacitor value. The MCP-6021 follower is powered by an analog bench power supply in the tests below. Direct op-amp drive models how the transformer will behave when used to isolate the audio outputs of a Softrock receiver. (Harmonic distortion and frequency response is not the end of the suitability requirement when used to isolate a Softrock receiver, of course. Amplitude and phase balance between two randomly selected KS transformers are also important but I have not yet looked at this aspect of these transformers.)

The plot below shows the improvement in harmonic distortion achieved when driven with a low impedance source (dotted line), compared with the 600 ohm source (solid line).



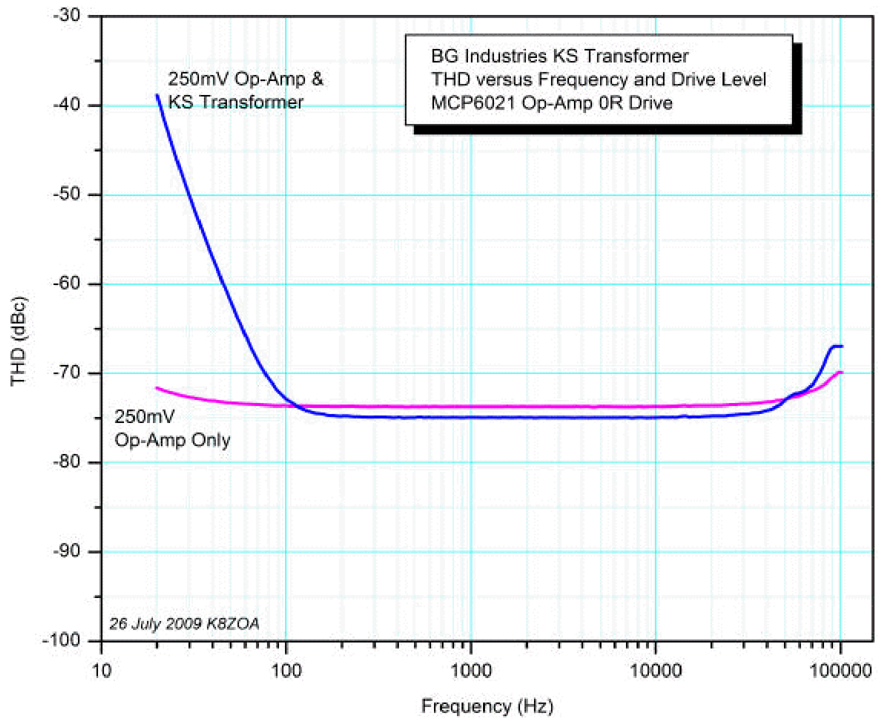
In fact, the improvement in THD obtained from low impedance drive is better than indicated in the plot above, as the low impedance results are limited by the test equipment and broadband noise from the op-amp and power supply. The plot below shows the measured low impedance transformer THD and the THD floor (dotted lines) when the transformer is removed and the op-amp output connected directly to the 8903B's input section.

Above a few hundred Hz, the test setup's noise and distortion floor limits the measurement.



I also looked at the harmonic distortion performance over a wider frequency range, 20 Hz to 100 KHz, with the results shown below.

In order to make meaningful harmonic distortion measurements over this wide frequency range, I had to operate the 8903B with the low pass filters switched out. (Earlier measurements used the 80 KHz low pass filter mode.) This increases the noise floor around 10 dB, as may be seen by comparing the plot above (80 KHz filter engaged) and the plot below. The plot seems to show the transformer improves the op-amp performance by 1 dB or so, but this is almost certainly a measurement artifact and should be disregarded.

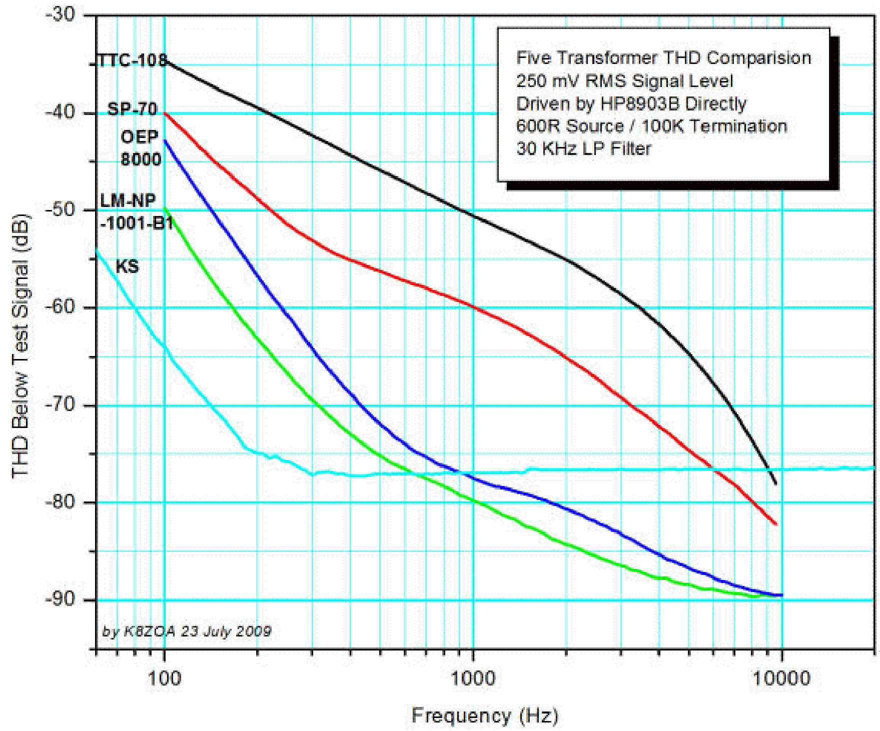


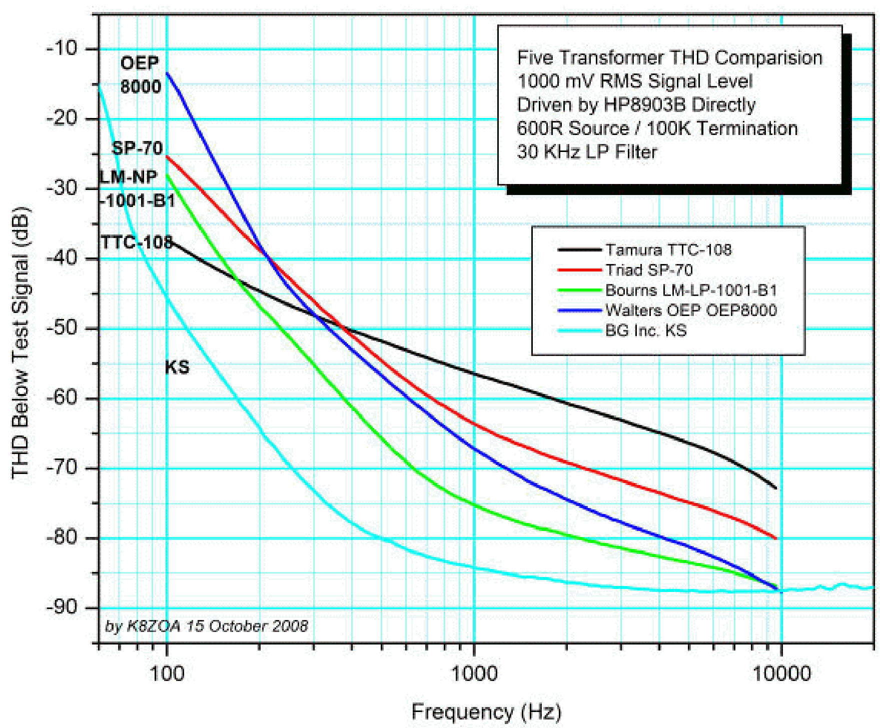
KS THD Comparison to Other Transformers

The two figures below compare the THD of five physically small transformers measured at signal levels of 250 and 1000 mV RMS.

At 1000 mV drive, the KS part is clearly superior to all the similar size transformers plotted, in some cases by 25 dB, in other cases by lesser amounts, but still superior.

At 250 mV drive, a different story emerges, with the KS part being superior up to 1 KHz with the THD then becoming constant at -77 dB. This is odd and is a performance not seen in other transformers studied. A similar plateau is seen at 100 mV in the KS distortion plot above.





How Does All This Relate to the K3 LINE OUT Audio Distortion?

How does this mass (or, some may think "mess") of data and analysis relate to Elecraft's use of a TTC-108 transformer in the K3's LINE OUT port?

I've demonstrated at http://www.cliftonlaboratories.com/elecraft_k3_receive_audio.htm that the K3's LINE OUT exhibits a odd-order harmonic problem, with the 3rd harmonic typically down 45 dB or so over a reasonable range of audio output levels. Further, similar levels of harmonic distortion are not present in the K3's headphone and speaker outputs. Between the data at that page and the information on this page, it's quite clear that the Tamura TTC-108 transformer is the source of the harmonic distortion, compounded by Elecraft's decision to drive the TTC-108 through a 604 ohm resistor.

There's no evidence that the TTC-108 is being driven into "magnetic saturation" at the audio levels available from the K3. Indeed, the B-H curves and THD data on this page show that the K3's maximum LINE OUT voltage level does not come close to moving the B-H curves into saturation or even into the saturation knee, particularly at the frequencies involved. Remember, magnetic saturation is a phenomenon of high signal levels and low frequenciesï¿½in the case of the K3, magnetic saturation of the TTC-108 is not possible, given the normal lower limit of communications receivers frequency response and the maximum output voltage.

Rather than from magnetic saturation, the TTC-108's mediocre harmonic distortion performance seems to be a product of its designers choice of magnetic core material and core size. The data presented on this page shows that similar size transformers, such as the Bourns LM-NP-1001, can provide 20 dB or so lower harmonic distortion, at least so long as the levels are kept down. Unlike the TTC-108, however, it is possible to drive the LM-NP-1001 into magnetic saturation, or at least the outskirts of saturation at levels not too far from normal, although only at frequencies below the normal communications receiver cutoff. The TTC-108's mediocre harmonic distortion performance is, moreover, compounded by the K3's use of 604 ohm series driver resistance.

With respect to the Stancor transformers studied, there is little to recommend them as a replacement for Elecraft's TTC-108.

The Jensen transformers embodied within the DIN-2LI package represent an extreme end of the price/performance curve with extraordinary performance at a price roughly 20 times the low end transformers. This is one example of "you get what you pay for" in the transformer world.

BG Incorporated's KS transformer demonstrates some oddities. At 1000 mV, for example, it shows excellent harmonic distortion from 100 Hz to 10 KHz, clearly superior to other low cost telephone transformers. Likewise, the KS transformer has very good frequency response. At lower drive levels, however, the KS part's THD plateaus for frequencies above 1 KHz and is not as good as certain of the other similar parts studied.