Audio Engineering Society

Convention Paper

Presented at the 111th Convention
2001 September 21–24   New York, NY, USA

Characterizing Digital Audio Transformers with Induced Jitter Histograms

Jon D. Paul, Vice President
Scientific Conversion, Inc.
Novato, California, 94947 USA
jonpaul@scientificconversion.com

ABSTRACT

Transformers are employed in digital audio systems primarily to reject common mode noise interference. A new test characterizes the interference rejection of a practical transmission system with a transformer at the receiver input. A sample set of the decoded frame sync clocks are accumulated by a statistical time interval analyzer. The analyzer calculates the mean value of the periods, the standard deviation (jitter), and provides a period histogram. The histogram and standard deviation establish a basis for comparing the high frequency interference rejection of various transformers and for quantifying the nature of the induced jitter. Test data are presented for 7 different types of transformers.

INTRODUCTION

Transformers are used in digital audio transmission primarily for rejection of high frequency common mode interference and for breaking ground loops. The Industry Standards [1,2,3] do not specify the transformer in great detail, and some [4] do not even require their use.

A previous paper by the author [5] described digital audio transformer parameters and their effect on transmission of signals. The bandwidth, pulse aberration and common mode rejection ratio (CMRR) were all shown to be important properties in choosing transformers for high quality transmission.

Various papers [6,7] have detailed the causes and effects of jitter in digital audio systems, however the effect of transformers in reducing jitter by virtue of their noise rejection properties has not been studied in detail. Conventional common mode rejection ratio (CMRR) measurements do not yield data directly applicable to practical digital audio transmission systems, especially when noise is present.

If a transformer has adequate bandwidth and low pulse aberration, but the system environment is noisy, then the CMRR of the transformer has substantial effect on overall system performance, especially on the jitter. Even if reclocking is used to reduce jitter effects, the contamination of the circuits ground and power planes via EMI and asynchronous common mode noise can have serious consequences in professional and broadcast applications.

This paper describes a sensitive technique for testing transformers for rejection of common mode noise and determining the transformer's contribution to overall system jitter in practical noisy environments. The transformer under test is placed between a transmission cable and a typical digital audio receiver. Common mode noise is intentionally injected into the cable. The clock recovered from the receiver is analyzed by a time interval counter with statistics, which measures the wide band jitter and provides a graphic display of a histogram of the period. Statistics of the period of the frame sync provide a sensitive measurement of transformer performance. A number of typical transformers were tested for conventional parameters as well as jitter histograms. The results show wide performance variations between commercially available transformers.

1. TRANSFORMER PARAMETER MEASUREMENTS

The various parameters that characterize transformers were reviewed in the author's previous paper [5]. The lumped constant parameters e.g. primary inductance and shunt capacitance affect the low and high frequency bandwidth, return loss and pulse aberration. Once these parameters are optimized, transmission fidelity depends on the cables, terminations and other system components. The effectiveness of the transformer in rejection of common mode noise and EMI is not so easily evaluated.

2. CONVENTIONAL MEASUREMENT OF COMMON MODE REJECTION

Direct measurement of common mode rejection of the transformer and receiver in the system of Fig. 1a is quite difficult. The receiver's differential amplifier inputs present a complex and somewhat non-linear common mode impedance to the transformer output. The high impedance means that insertion of scope probes or other measurement devices at the receiver inputs will result in substantial change in the common mode impedance and greatly affect the measurement results.

Transformer measurements carried out with network analyzers cannot accurately model practical systems. Figure 1b represents the basic method of testing the CMRR using either a network analyzer or separate oscillator and voltmeter.

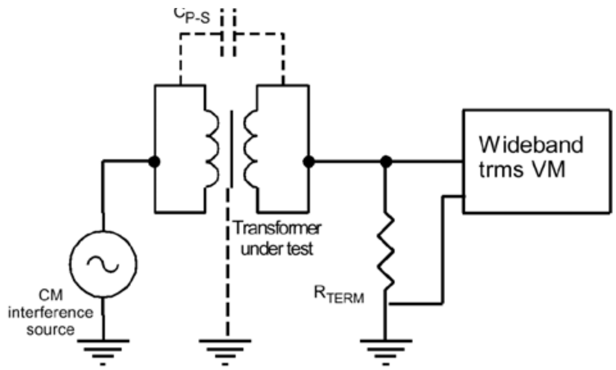


Fig. 1b. Conventional common mode rejection test.

A leveled oscillator is connected to both sides of the primary and the secondary common mode voltage is detected by connecting both sides of the secondary to a load impedance and voltmeter. If a shield is present in the transformer, it is returned to ground. The CMRR is the ratio the secondary to primary common mode voltage.

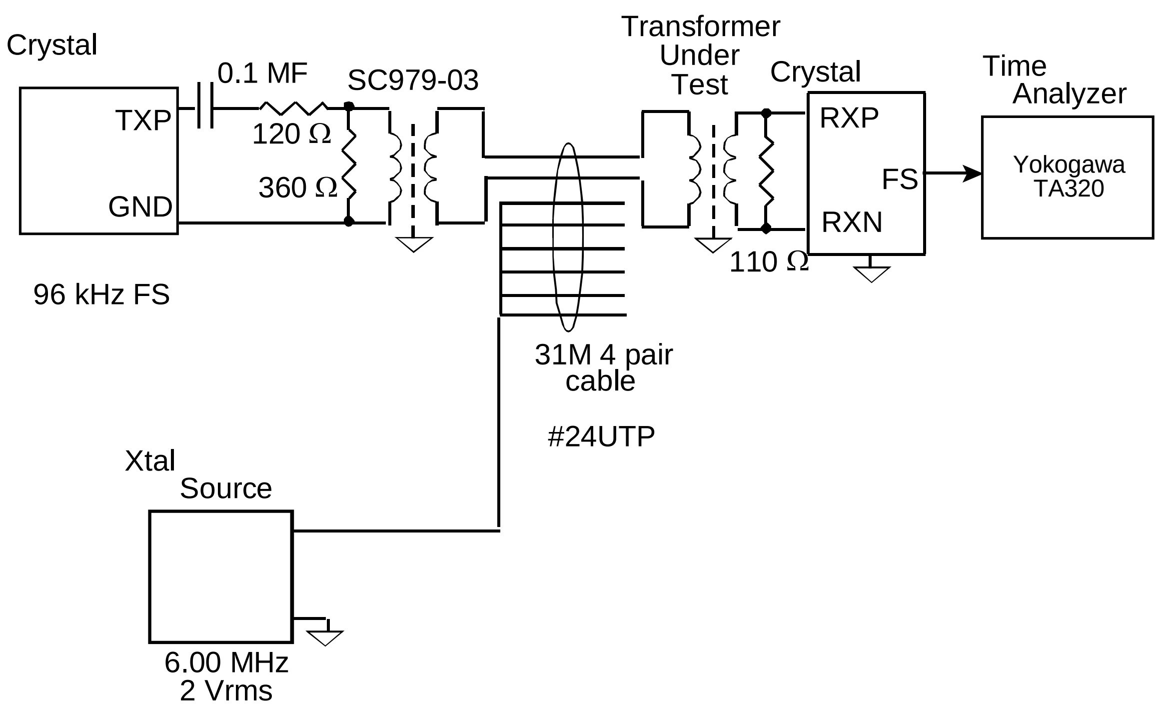
The problem is that suitable network analyzers, e.g. HP 3577b, have input impedances of 50 or 75 Ω, which is orders of magnitude lower than the differential receivers used in digital audio systems.

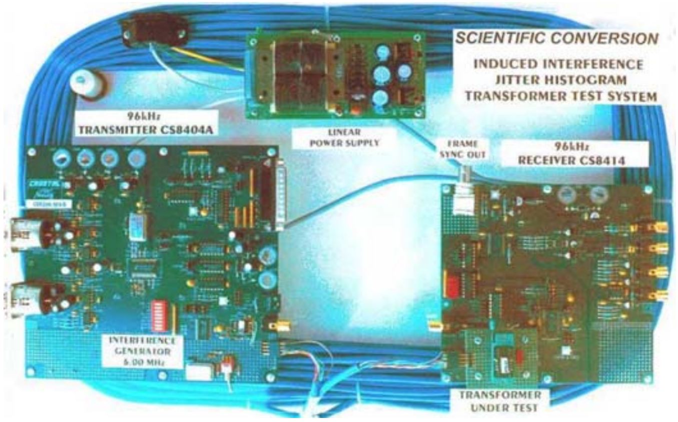
It would seem that that just checking the primary to secondary capacitance of the transformer characterizes its CMRR if the CM impedance was known. Unfortunately, this capacitance measurement depends on the test fixture and connections, as well as the treatment of any shields present in the transformer.

The best transformers available have a guarded capacitance of ~ 1 pF making this a difficult and somewhat inaccurate test. Even when the primary to secondary capacitance is exactly known, other factors will affect the calculated CMRR: the effectiveness and inductance of the internal shield (if present), the unbalance of the windings causing common mode to differential mode conversion, the assumed CM impedance, etc.

The common mode impedance presented to the transformer secondary by the differential receiver is not easy to characterize, as the differential amplifier common mode impedance values are comparatively high (many kΩ) and complex (input capacitance + bias current). These parameters depend on active components in the IC and are not tightly specified (if at all) by the manufacturers.

Thus the effective in-circuit common mode noise rejection of the transformer cannot be directly inferred from either conventional CMRR measurements nor accurately calculated from the primary to secondary capacitance.





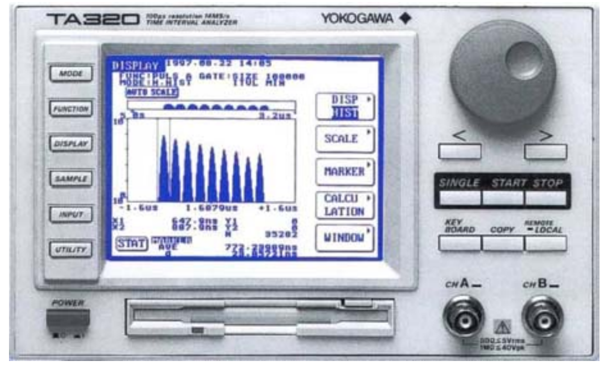


Fig. 2c. Time interval analyzer

3. NEW MEASUREMENT METHOD

The goal of the new test was to create a measurement that directly tests the effect of the transformer on received clock jitter due to a common mode noise. It is easy to setup and use and simulates a practical environment, while showing the differences between transformers with maximum sensitivity.

Fig. 2a shows a typical implementation of a system developed over a period of 5 years for testing transformers with induced noise and jitter histograms. Fig. 2b is a photograph of the completed test fixture. An AES3 transmitter such as the Crystal CS-8404A is clocked at a frame sync rate of 96 kHz. The output is coupled to a high quality reference transformer through appropriate resistors and capacitors. The transformer provides balanced 110Ω AES3 signals to one pair of a four pair cable. The cable specifications follow:

Model	Belden 1538A
Length	31m
Wire	#24 ga. UTP PVC twisted pair
Inductance	13.38 uH/M per conductor
CM Capacitance	62.58 pF/M each to all others
Resistance	86.13 mΩ/M per conductor

The common mode interference is generated by an oscillator connected to all conductors of the remaining three pairs of the cable at the transmit end. The far end of the cable pair carrying the AES3 signal is connected to the primary of the transformer under test. If the transformer has a shield, it is connected to the receiver ground plane. The transformer secondary drives the receiver differential inputs with a 110 Ω termination resistor across the secondary.

A number of different interference waveforms and frequencies were tested to obtain a maximum of common mode interference sensitivity at a realistic level and frequency. The interference frequency must not be a multiple or sub-multiple of the 96 kHz frame sync e.g. 6.144 MHz. The most sensitive test was with an interference frequency of 6 MHz, which is 62.5 x 96kHz (FS). The reason is that 6 MHz gives a beat frequency of 48 kHz, which is just at the half sample rate, thus causing maximum sensitivity to the induced jitter. The tests in the balance of this paper are made with a 6.00 MHz square wave, 2.0 VRMS applied as described above.

The receiver IC chosen is a Crystal 8414, because of its popularity in current equipment designs and because its architecture does not reclock the frame sync. The frame sync output is connected to the time interval analyzer shown in Fig. 2c, Yokogawa TA320. This analyzer has 100 ps resolution and can calculate all statistics of the signal period, and display a histogram of the distribution of periods. Many other statistical counters and time interval analyzers could be used, available from firms such as Hewlett Packard, Stanford Applied Research, etc.

We configured the analyzer to measure the period of the frame sync on adjacent positive transitions, gather a sample set of 3500 samples and calculate the mean and standard deviation of the period. The standard deviation corresponds to the wide band jitter. This analyzer can only measure peak to peak rather than peak jitter, therefore the test data will be a factor of 2 greater than the jitter figures from industry standard measurement techniques [6,7]. The typical sample set corresponds to ~ 35 ms sample time, making the test insensitive to low frequency jitter sources. The beat frequency of 48kHz yields a very sensitive test. The histogram display shows the number of samples as a function of time interval, centered on the mean period.

4. ISOLATION OF TRANSFORMER FROM OVERALL SYSTEM JITTER

Each component of the system will make a contribution to the observed jitter of the received frame sync, e.g. bandwidth limitation affecting the eye pattern and mode conversion from common mode to normal mode due to imbalance at the transformer or receiver input stage. Fig. 3 shows the mathematics relating each component of a system to the overall jitter. We seek to isolate the effects of the transformer from that of other system components.

$V \approx$ variance of period

$\sigma \approx$ standard deviation of period $\approx$ wideband jitter

$V_1, \sigma_1 \approx$ variance, std. dev. of component 1

$V_2, \sigma_2 \approx$ variance, std. dev. of component 2

$V_T, \sigma_T \approx$ variance, std. dev. of system 1 + 2

(1) $$V_T = V_1 + V_2$$

(2) $$\sigma_T = \sqrt{V_T} = \sqrt{V_1 + V_2}$$

(3) $$\sigma_T = \sqrt{\sigma_1^2 + \sigma_2^2}$$

(4) $$\sigma_1 = \sqrt{\sigma_T^2 - \sigma_2^2}$$

Fig. 3. Relationship of system to component jitter.

For each transformer to be tested, we take a data set with the interference source running and a second measurement with the interference source turned off.. We can show [8] that for statistically independent measurements we have a linear system and superposition allows the component variances to add as in equation (1) to give a total system variance.

Standard deviation is the square root of the variance as shown in equation (2). Therefore, it is the square root of the sum of each component's standard deviation. Equation (3) expresses this as standard deviation and equation (4) derives the desired system component's standard deviation as a square root of the differences between the squares of the overall system and the other components of the system.

If we define the transformer as component 1 and the remainder of the system as component 2, the transformer's contribution to the overall jitter measurement, "induced jitter", is symbol J_T.

5. HISTOGRAM TEST RESULTS

An ideal jitter histogram would have every period in the sample set at precisely the desired value, producing a histogram with a single line in the exact center. A practical measurement with jitter present has various periods producing a wider pattern, which would ideally be of Gaussian shape. As the jitter increases, the Gaussian pattern will widen. Tests with very poor CMRR transformers will have widely disbursed histograms.

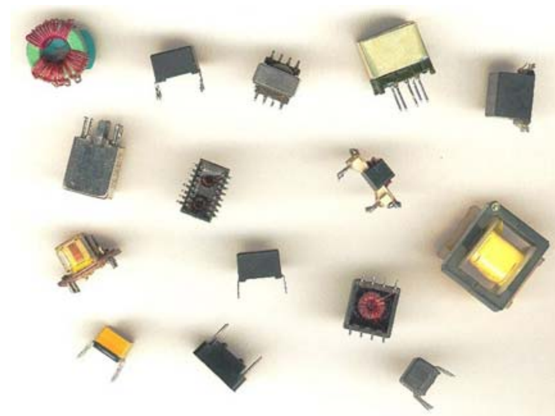


Fig. 4. Typical AES/EBU transformers.

A great variety of transformers intended for digital audio transmission are available as shown in Fig. 4. We selected 7 typical transformers to represent a wide selection in size, quality, construction and parameters. All were tested for conventional parameters, and jitter histograms. The results below show the histogram and the induced jitter, J_T for each transformer.

Please note that the ordinate for all histograms is number of samples. Initially, a test was made with no transformer at the receiver input, to show the common mode rejection of the digital audio receiver itself, shown in Fig. 5. Fig. 6 represents the worst transformer of the group: a plastic injection molded unit with high primary inductance and high primary to secondary capacitance. Fig. 7, 8 and 9 are three smaller transformers of similar physical construction with progressively decreasing number of turns, inductance and primary to secondary capacitance. All of these exhibit a greatly disbursed histogram and high J_T.

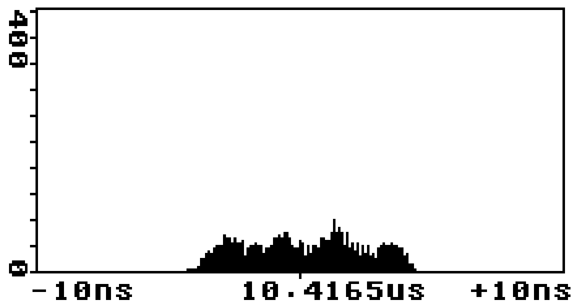


Fig. 5. Jitter histogram without transformer, J_T = 4,638 ps.

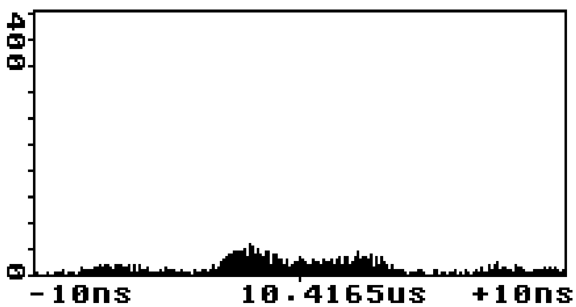


Fig. 6. Jitter histogram with transformer #1, J_T = 3,617 ps.

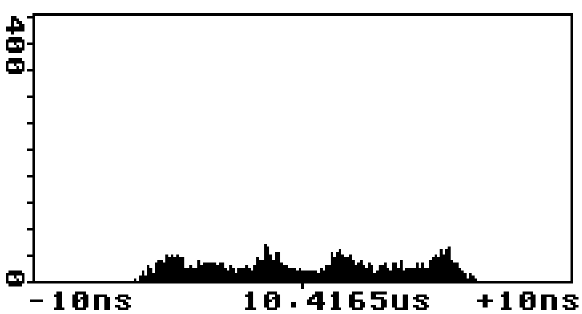


Fig. 7. Jitter histogram of transformer #2, J_T = 2,893 ps.

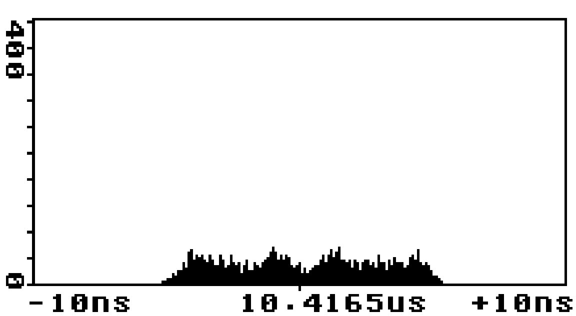


Fig. 8. Jitter histogram of transformer #3, J_T = 2,304 ps.

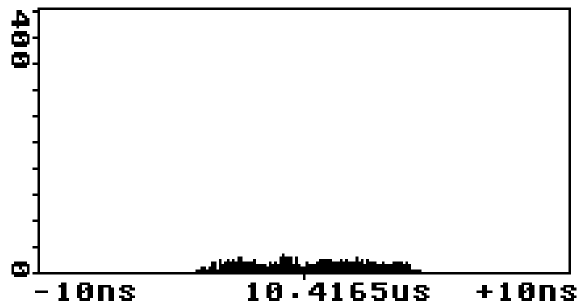


Fig. 9. Jitter histogram of transformer #4, J_T = 2,242 ps.

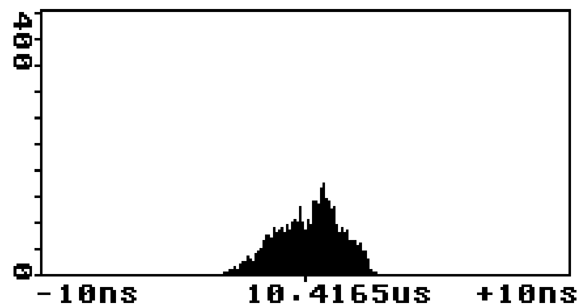


Fig. 10. Jitter histogram of transformer #5 (unshielded), J_T = 1,241 ps.

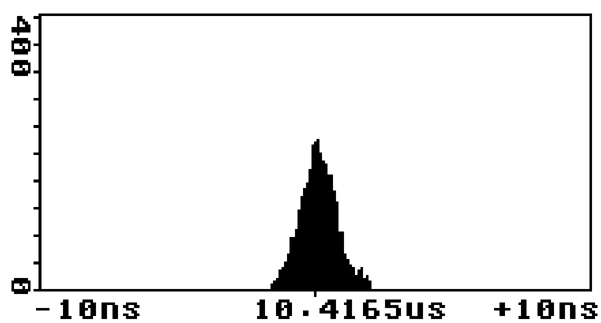


Fig. 11. Jitter histogram of transformer #5 (shielded), J_T = 703 ps.

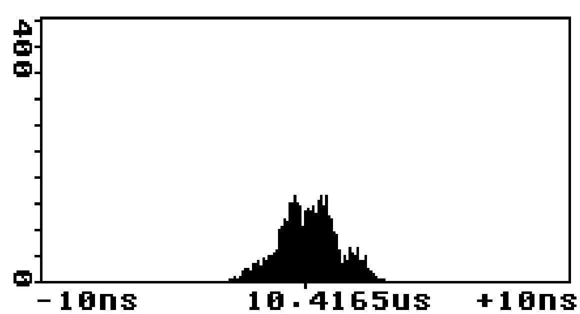


Fig. 12. Jitter histogram of transformer #6 (unshielded), J_T = 1,147 ps.

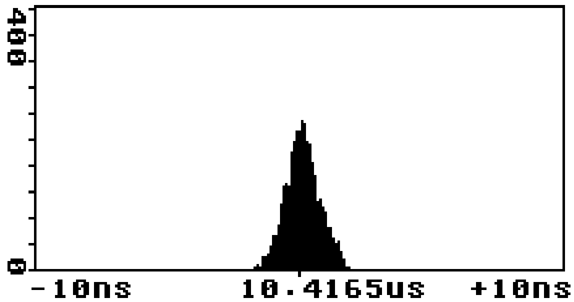


Fig. 13. Jitter histogram of transformer #6 (shielded), J_T = 676 ps.

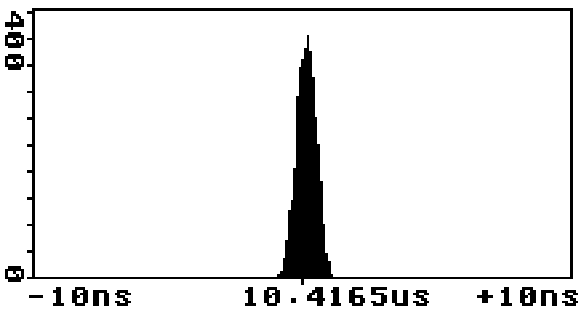


Fig. 14. Jitter histogram of transformer #7, J_T = 368 ps.

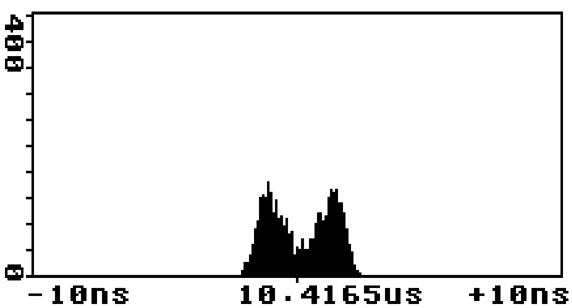


Fig. 15. Jitter histogram of transformer #8, J_T = 1,217 ps.

Fig. 10 is a transformer optimized for sample rates 32...48 kHz with a shield, which was left floating. The histogram is closer to Gaussian.

Fig. 11 is this same transformer with its shield connected, showing a reasonable J_T and better histogram pattern.

Fig. 12 is a surface mount transformer optimized for medium sample rates with its shield floating.

Fig. 13 is the same model with the shield connected. The histogram is near ideal and the J_T is quite good.

Fig. 14 is a transformer optimized for 96…192 kHz use, with lowest possible capacitance. This has the best J_T of the group tested, and a nearly Gaussian histogram.

Fig. 15 is an unusual histogram of a poor quality transformer which shows 2 sets of Gaussian shapes, displaced from the center by substantial amounts.

6. CORRELATION OF J_T WITH CONVENTIONAL PARAMETERS

Conventional parameters including primary magnetizing inductance, primary to secondary capacitance and leakage inductance were checked for each transformer using a multi frequency bridge. Conventional common mode noise rejection was calculated from the capacitance at 6.0 MHz and with a 110 Ω CM impedance. Return loss was measured at frequency 500 KHz and 6 MHz using a Hewlett Packard 3577A network analyzer in a 50 Ω environment. The induced jitter J_T was calculated as described above in Sec. 4.

Fig. 16 shows a scatter plot of all of the above measurements with the plot ordinate being transformer jitter J_T and the abscissa showing each of the other parameters normalized. The plot shows in sequence six parameters: primary-secondary capacitance, primary inductance, leakage inductance, return loss at 6 MHz, low frequency corner, and high frequency corner. Each parameter is normalized to the highest value obtained amongst all seven transformers and is plotted as a function of the jitter measurement J_T.

The set of jitter measurements Jt correlated well with measured guarded primary to secondary capacitance as shown in Fig. 17.

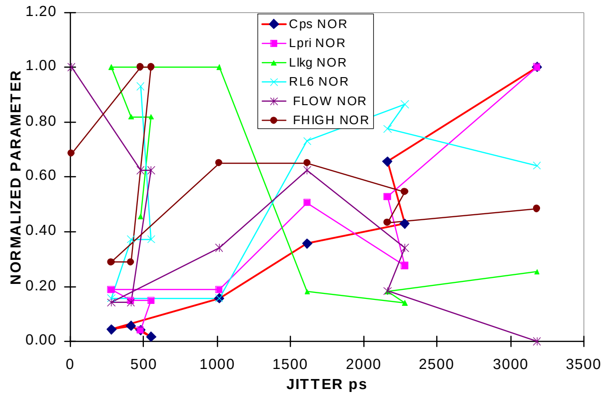


Fig. 16. Correlation of various transformer parameters vs. jitter.

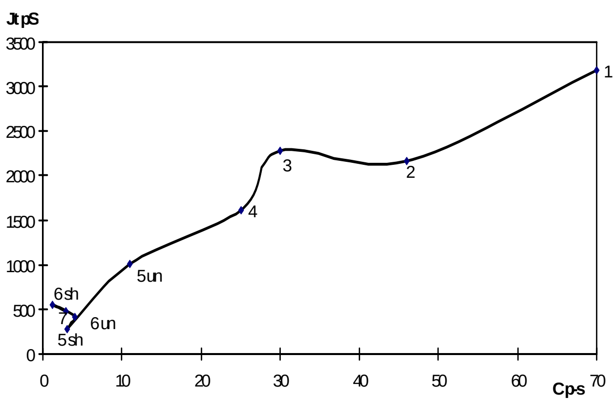


Fig. 17. J_T vs. $C_{pri-sec}$.

Fig. 18 is a comparison chart of the seven transformers tested and appropriate measurements using no transformer in the first column. Units 5 and 6 have shields and were tested both with the shield floating (Un Sh) and grounded (Sh). The chart shows the wide variation in performance and the insensitivity of jitter to most certain conventional parameters except primary to secondary capacitance.

CONCLUSION

Conventional transformer tests do not adequately characterize high frequency common mode rejection effects in which are critical practical applications. A new test, using induced common mode noise and jitter histograms, maximizes the differences between transformers and provides graphic display of the effects of transformers on jitter in noisy environments.

The results suggest that all balanced applications and industry standards should require the use of a transformer to provide acceptable CMRR and high frequency EMI rejection. The author suggests that standards not presently requiring transformers be amended to do so.

Transf		ref 31M cable	1	2	3	4	5 Un Sh	5 Sh	6 Un Sh	6 Sh	7
Primary Inductance	µH	-	5515	2910	1522	2790	1042	1042	820	820	230
Capacitance P - S	pF	-	70	46	30	25	11	3.1	4.0	1.15	2.90
Leakage Ind	µH	-	0.42	0.30	0.23	0.3	1.65	1.65	1.35	1.35	0.75
LF cutoff F_{LOW}	kHz	DC	2.2	4.1	7.5	4.1	1.7	1.7	7.5	7.5	12.0
HF Cutoff F_{HIGH}	MHz	29.0	26.0	32.7	39.0	39.0	17.3	17.3	60.0	60.0	41.1
RMS Jitter Jt 6 MHz 2V	pS	4638	3178	2161	2278	1613	1013	279	413	553	479
Calc.CMRR @ 6.0MHz 110 Ω	dB	-	11.7	14.9	18.9	20	27	38.7	36	46.8	39.2
Return Loss 500kHz	dB	-	29	30.2	31.7	30.5	25	25	30.3	30.3	33.8
Return Loss 6 MHz	dB	-	18.6	22.5	25.1	21.2	4.6	4.6	10.8	10.8	27

References

[1] IEC60958 - 1, 3, 4 Digital Audio Interface, International Electrotechnical Commission, Geneva.

[2] AES-3id1995, AES Information document for digital audio engineering - Transmission of AES3 formatted data by unbalanced coaxial cable, Audio Engineering Society, New York, NY, USA (1995).

[3] EBU 3250, (Ed. 2 1992) European Broadcasting Union

[4] AES3-1992, AES Recommended practice for digital audio engineering - Serial transmission format for two-channel linearly represented digital audio data, Audio Engineering Society, New York, NY, USA (1992).

[5] Paul, Jon D., "The Effect of Transformers on Transmission of Digital Audio Signals," Preprint 4840, 105th AES Convention, San Francisco, September 1998.

[6] Dunn J., McKibben B., Taylor R. & Travis C. "Towards Common Specifications for Digital Audio Interface Jitter," Preprint 3705, presented at the 95th AES Convention, New York, October 1993

[7] Dunn, Julian, "Jitter Theory," *Audio Precision Newsletter*, vol. 14, no. 1 (1999), "Jitter Theory - Part Two," Audio Precision Newsletter, vol. 15, no. 1 (2000).

[8] Handbook of mathematics, Bronstein and Semendjajew, ISBN 3 87144 492 8, Teubner Verlag, Leipzig