Testing ADCs Used in High-Speed High-Resolution Digital Waveform Recorders

Santosh C. Vora and L. Satish

Abstract—**Testing and calibration of high-speed high-resolution digitizers (i.e. the ADC) used in HV impulse measurements is mandatory as per modern metrology, especially, in intercomparison and reference measurements, where extremely high levels of accuracies are demanded. Such testing services are, at the present moment, not being offered in the country. Digitizer or oscilloscope manufacturers quote exorbitant prices for providing the same, as in most cases the equipment needs to be sent overseas. Also, there exists no National Standard for such tests. Despite this, HV labs in the country use digital impulse measuring systems, and so are compelled to undertake this costly exercise, on expiry of the test certificate. This was the prime motivation.**

This paper demonstrates, for the first time in the country, how comprehensive testing of high-speed high-resolution ADCs (as per IEEE 1057 and IEC 61083-1) can be achieved, with available signal sources and equipment. Almost all the tests described therein have been implemented and results for an 8-bit digital oscilloscope (Yokogawa DL 1540) and a 10-bit real time digitizer (Sony Tektronix RTD 710A) system are presented.

Index Terms—**ADC, Analog-to-Digital Converter, IEEE 1057 and IEC 61083-1, Static and Dynamic Testing.**

I. Introduction

There has been a substantial growth in the use of digital recording and signal processing techniques in the field of high voltage impulse testing and measurements [1]. Since, these digital systems operate entirely differently compared to their analog predecessors, and the levels of accuracies expected from them are extremely high (especially in calibration and testing of reference or approved impulse measuring systems), there arises a necessity to institute procedures for ascertaining whether they are indeed functioning as per requirements. One way of ascertaining this is to do a calibration. Standards like IEC 61083-1, IEEE 1057 and IEEE 1122 [2, 3, 4] outline tests and procedures to determine various characteristics of the waveform recorder, from which, its performance can be assessed.

In an impulse measuring system, the digitizer (or ADC) is the most sensitive and important component, because it dictates accuracy of the measured impulses, viz. peak voltages, impulse scale factors, time parameters etc. Despite great advances in chip design and technology used during its manufacture, actual ADC characteristics are far from ideal. There exist several types of deviations from ideal characteristics, and these are popularly referred to as, static and dynamic non-linearities, offset and gain errors, aperture uncertainty, and so on [5, 6, 7, 8, 9].

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Depending on the application, some or all of these could acquire greater significance. In impulse measurements, the dynamic and static characteristics of an ADC play a vital role and are the accepted benchmarks to judge its usability.

Determination of these ADC characteristics requires highly precise and repeated applications of various types of signals (which by themselves must be spectrally very pure and stable) coupled with accurate measurements, followed by data storage and processing. Furthermore, it poses a constraint that, metrology-quality, computer controlled signal sources are necessarily available. This inherent requirement makes testing and calibration not only a complex operation, but also an expensive affair. Currently, such facilities are NOT being offered within the country, although a few facilities are available in testing labs abroad. Further, calibration is valid for a limited period and any repair/change in measuring set-up or equipment automatically mandates a fresh calibration.

Keeping these aspects in mind, a work was undertaken to create such a test facility, using available equipment. The initial goal was to explore its feasibility and importantly gather experience in doing such tests. When equipment and signal sources of required specifications become available in future, actual calibration of waveform recorders can be performed. Quite naturally, the environment under which such a platform could be built had to support simple and user-friendly interface or communication between the host computer and other instruments via GPIB. The project was implemented in VEE Pro 6.01, a graphical programming language, specially suited for such tasks.

Detailed descriptions of various ADC errors, its origin, definition, etc., are not included due to brevity of space. However, the reader is referred to literature, such as in [3, 4, 5, 8, 9, 10]. A brief description of experimental set up, followed by details of various tests implemented and the results obtained are discussed. Details can be found in [11].

II. Test Set Up And Signal Sources

Two digital waveform recorders namely, a 10-bit real time digitizer (RTD 710A, Sony Tektronix) and an 8-bit digital storage oscilloscope (DL 1540, Yokogawa) were tested. Fig. 1 shows schematic of the test set up. A programmable arbitrary waveform generator (AWG) 33250A (Agilent technologies), Reference Impulse Calibrator (RIC 422, Haefely Inc.) and a unit step generator (developed in the department) were used as the signal sources. All the tests implemented, except step calibration, are fully automated under computer control, via GPIB interface. The following tests, as per IEC 61083-1 and IEEE 1057 were implemented.

- Static Non-Linearity
  - Integral Non-Linearity (INL)
  - Differential Non-Linearity (DNL)

- Dynamic Differential Non-Linearity (DDNL)
- Beat frequency,
- Sine wave curve-fit
- FFT
- Impulse calibration
- Step calibration

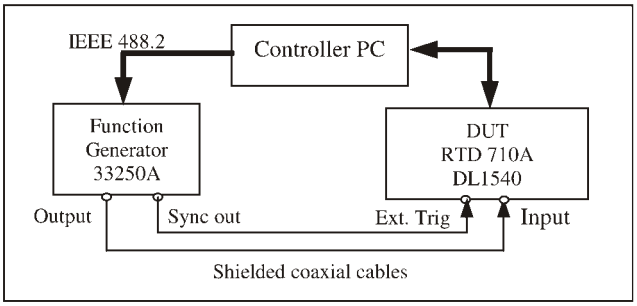

Fig. 1. Schematic of test set up.

The first ADC system tested was a digitizer, RTD 710A, which employs a 10-bit ADC (configured as two 5-bit sub-ranging flash ADCs) with a highest sampling frequency of 100 MSa/s in normal mode (Msa/s = Mega-Samples/s) and 200 MSa/s in high-speed mode (when only Channel-1 is used). It has a maximum memory of 256K, if one channel is used. The second system was an 8-bit digital storage oscilloscope, DL1540, with highest sampling frequency of 200 MSa/s in normal mode and maximum memory of 10032 points. A brief description of the signal sources is given below-

- The arbitrary waveform generator (33250A) has a 12-bit DAC (including sign), and a memory of 64K points (switchable in fixed steps). It can generate a variety of standard waveforms and also supports user-defined arbitrary waveform generation. The amplitude range has an accuracy level of (±1% of setting ±1mVpp). This was used to perform static and dynamic test, beat-frequency test, sine-wave curve-fit test and FFT test.
- The Reference Impulse Calibrator (RIC 422) is a fully calibrated instrument traceable to PTB, Germany, and is capable of generating full and chopped Std LI (both short and long front), in addition to other waveforms. The impulses are generated in a user-specified sequence, controlled via GPIB, and used for impulse calibration.
- The unit step generator (USG) is a non-programmable signal source that generates a step pulse of ~350 V, and has a rise time of ~2 ns, with a repetition rate ~50Hz, and used for step calibration.

III. Results

A. *Static Tests (INL and DNL)*

This is a type test and used to ascertain ability of ADC to acquire slow varying signals. INL and DNL derived from this test are regarded significant, as they indicate presence of bit-level anomalies and code transition levels, which in-turn dictates accuracy of measured impulses.

The test procedure involves application of at least five levels of DC voltage corresponding to each discrete level of vertical resolution. An n-bit ADC has 2^n discrete levels. So, a DC voltage of (1/5) * N * 2^{-n} * FSV is applied to the recorder low voltage input, where N is varied from 1 to 5 * 2^n, and FSV is full-scale voltage. So, for 5V range in RTD 710A, 5120 DC voltages, each incremented by 0.9766 mV have to be sequentially applied (and it takes close to 3 hours under computer control). Each applied DC waveform has to be acquired and mean of at least 100 samples calculated and the quantization or transfer characteristic obtained. INL and DNL are determined from this characteristic. The INL and DNL measured for a given range are, in general, representative for all ranges.

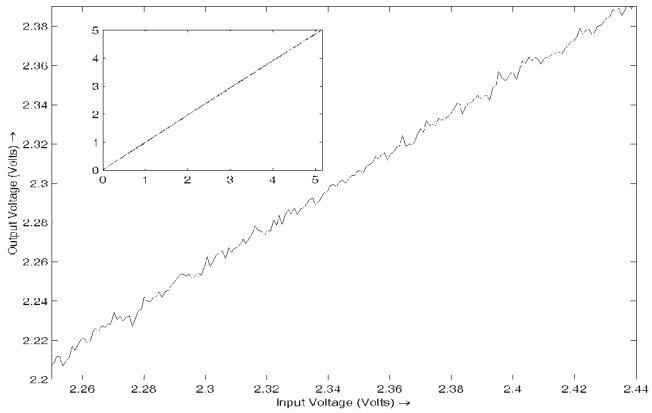

Fig. 2(a) Transfer characteristic of RTD 710A, 5V input range.

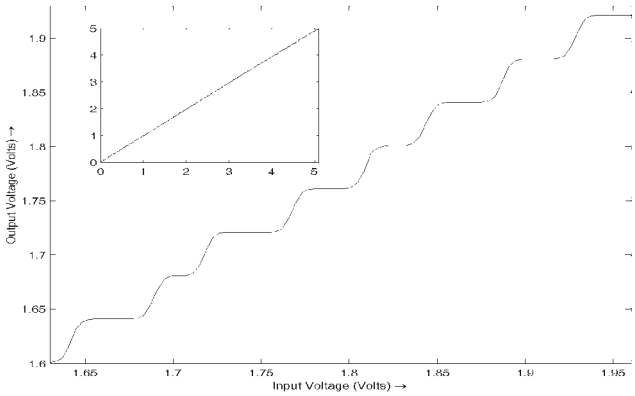

Fig. 2(b) Transfer characteristic of DL 1540, 5V input range.

Fig. 2(a) and 2(b) are the transfer characteristic of RTD 710A and DL 1540 (for 5V range) respectively. Fig. 3(a) is the corresponding INL and DNL characteristics of RTD 710A. These match very well with that reported in literature. The INL and DNL for DL 1540 are shown in Fig. 3(b).

B. *Dynamic Tests*

Dynamic test are useful to characterize ADC performance at very high rates of change of input, and hence considered as the most significant for impulse measurements. The histogram test, sine wave test, beat frequency test and FFT test are used to determine several aspects of ADC dynamic performance. While some of these tests are mandatory, the rest are only performance-checks, and yield a qualitative description.

B.1. Histogram Test (DDNL)

This test is done by recording ADC output for various input signal slopes, followed by computing histogram to indicate the

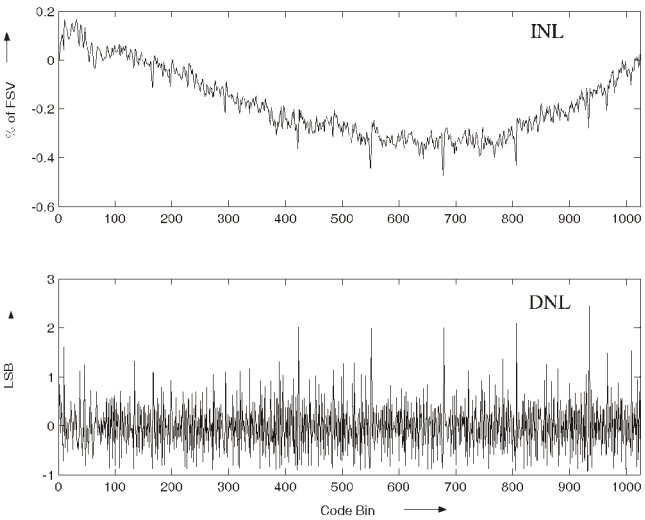

Fig. 3(a) Static characteristics of RTD 710A

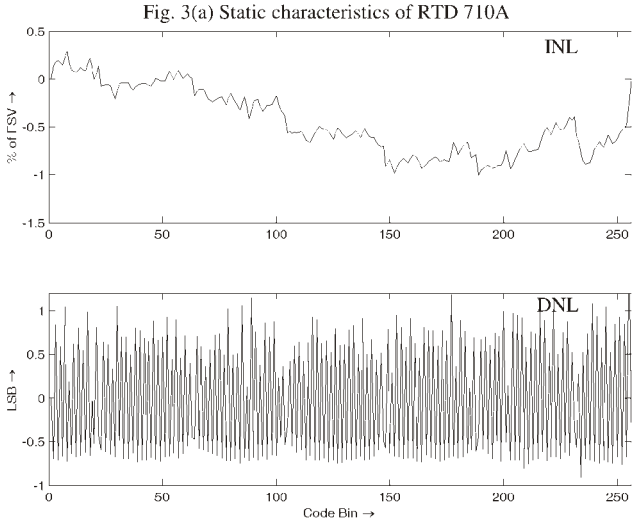

Fig. 3(b) Static characteristics of DL 1540

number of occurrences of each digital code. Any deviation of measured histogram from the corresponding ideal distribution indicates various errors (referred to as holes and chimneys). Both sine wave and triangular-wave are prescribed stimulus for this test, and debate about which one is better continues. Sample results for both these inputs are presented in Fig. 4(a) and 4(b) for RTD 710A, at 0.95MHz (sine wave) and 0.95MHz (triangular wave) respectively. Fig. 5(a) and 5(b) are histogram results for DL 1540 at 1.074218MHz (sine wave) and 878.90625kHz (triangular wave) respectively. The test frequency must be non-harmonically related to the sampling frequency (hence the above choices), in addition to meeting a few other constraints.

B.2. Sine Wave Test

Sine wave test involves application of a stable, pure sine signal to DUT and then fitting a mathematical sine function to the record of digital data acquired by the instrument. It yields a "global/qualitative" description of the sampling errors in a waveform recorder. This means, the recorder's errors are all averaged together to compute one numerical value, viz. the Effective Number of Bits (ENOB, also called equivalent bits), which is representative of the overall performance accuracy of the recorder. The point-by-point differences between the calculated best-fit sinusoid and digital record are taken as actual instantaneous errors, while the difference between the calculated sinusoid and the nearest digital level are taken as the instantaneous error of an ideal digitizer.

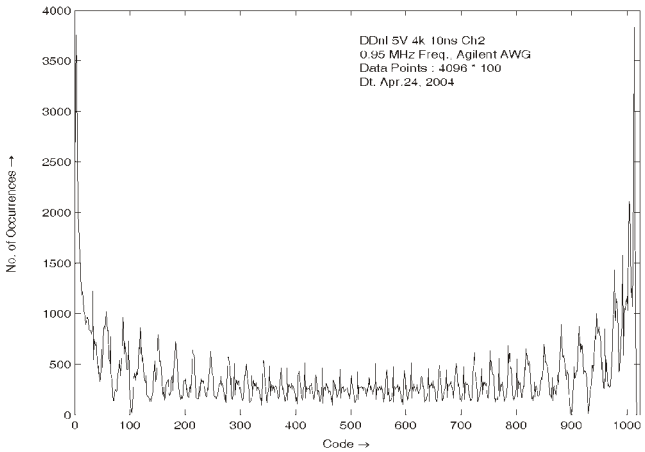

Fig. 4(a) Histogram test with SINE WAVE as stimulus (RTD 710A)

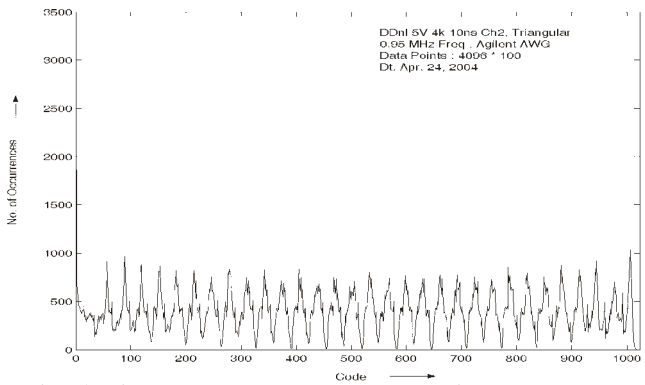

Fig. 4(b) Histogram test TRIANGULAR WAVE as input (RTD 710A).

A sample result of sine wave test done on RTD 710A is included in Fig. 6, for an input frequency of 1.074218MHz (as per IEEE 1057). The fitted curve (3-parameter fit), raw data and residue are shown. The ENOB at this frequency was evaluated as 6.6115.

B.3. Beat Frequency Test

Beat frequency test is a qualitative test for ADCs' dynamic performance and may be used to quickly judge whether or not there exist any gross problems. This test helps in determining differential non-linearities and missing code very precisely at high frequencies. The differential non-linearities show up as horizontal lines, where as gaps in the plot indicate missing codes. In this test, a full-scale sine wave is applied to the ADC. The input signal is offset slightly in frequency from the sampling rate. This frequency offset is selected such that, on successive cycles of the input sine wave, the ADC output ideally would change by 1 LSB at the point of maximum slope. Successive samples of the waveform steps slowly through the sine wave, as a function of the small difference, or beat, frequency.

Fig. 7(a) and 7(b) are the results at 10.00311MHz (sampled at 10MHz) for RTD 710A and 1.0012434MHz (sampled at 1MHz) for DL 1540 respectively.

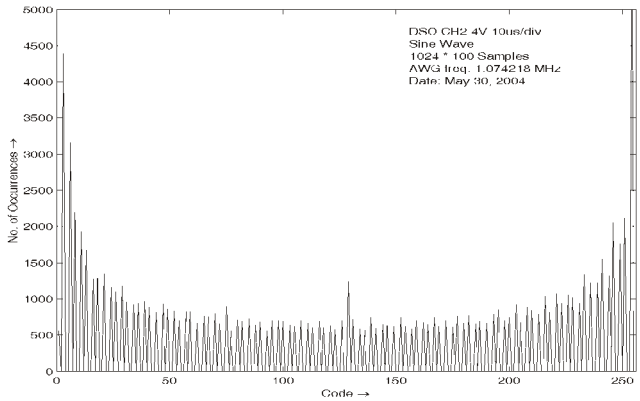

Fig. 5(a) Histogram test with SINE WAVE as stimulus (DL 1540)

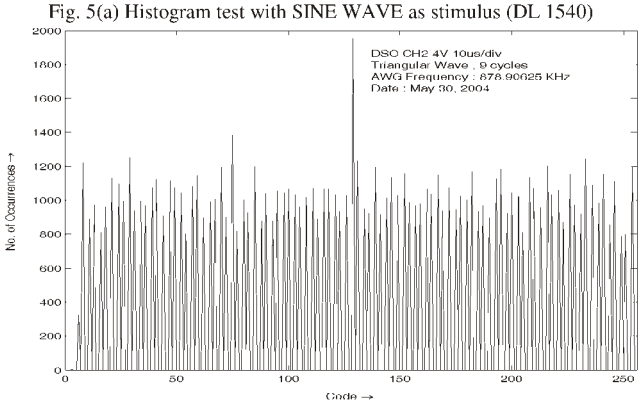

Fig. 5(b) Histogram test with TRIANGULAR WAVE as input (DL 1540)

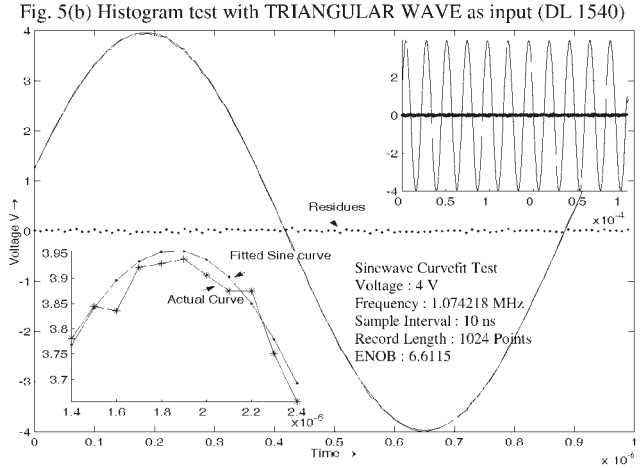

Fig. 6 Sine wave Curve Fit (RTD 710A),

B.4. FFT Test

Output samples from an ADC may be processed with a discrete Fourier transform (DFT) algorithm to define its linearity and noise properties in the frequency domain. The spectrum of ADC output will contain the input sine wave, quantization error, and any harmonic distortion caused by integral non-linearity. The combined effect of noise floor, harmonic distortion and spurious errors are reflected in the ADC's RMS signal-to-noise ratio, which can be derived from the DFT of magnitude spectrum. The signal energy is determined by summing energy in all the bins associated with the fundamental. It is a qualitative test.

A full-scale sine wave of a properly chosen frequency is applied to the ADC under test. A low-pass filter can be incorporated to ensure a spectrally pure input. A 1024-point record sampled at a maximum sampling rate is taken and stored. The DFT is used and a spectrum of magnitude and frequency plotted.

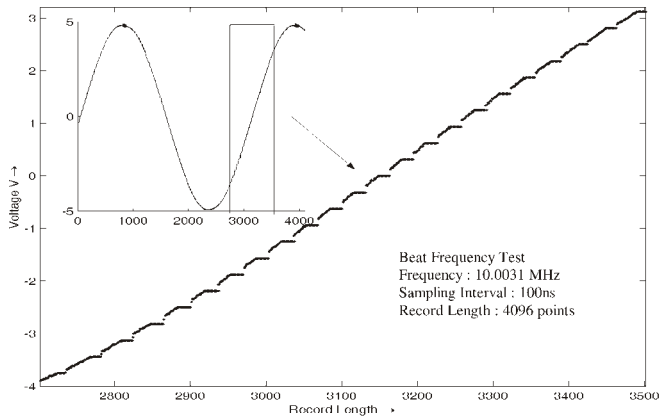

Fig. 7(a) Beat Frequency Test (RTD 710A)

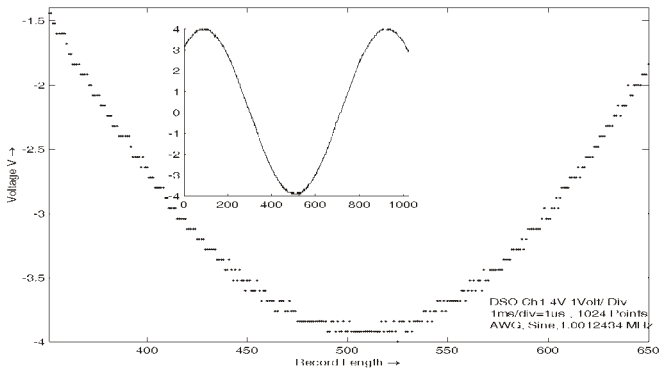

Fig. 7(b) Beat Frequency Test (DL 1540)

Fig. 8(a) and 8(b) are the results for a input sine wave of 5.3711MHz applied to RTD 710A and for a 1.074219MHz applied to DL 1540 respectively. The SNR for the two systems are 64.47dB and 73.5924dB respectively.

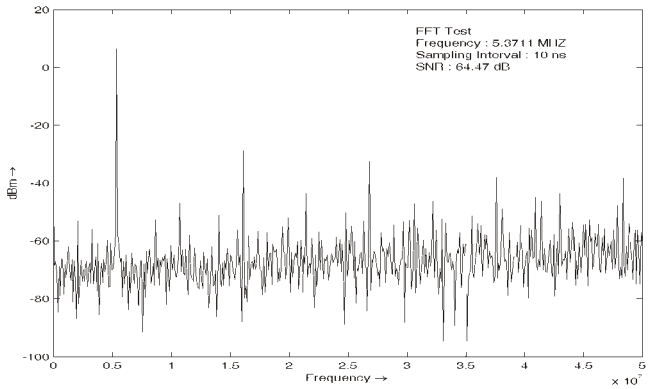

Fig. 8(a) FFT Test (RTD 710A)

C. *Step Calibration*

Some of the most revealing measures of the waveform recorder's dynamic performance can be computed from its step response. These not only include such time-domain parameters as impulse response, transition duration (rise time), settling-time and overshoot, but also frequency domain parameters such as bandwidth, frequency response and gain error etc.

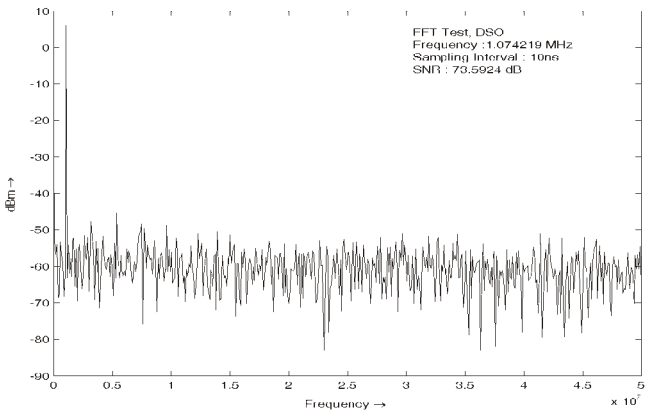

Fig. 8(b) FFT Test (DL 1540)

When a step, whose rise-time is shorter than the sampling interval of the digitizer, is applied to the digitizer, it will record either one or zero points on the transition, and if a point is recorded on the transition, its value will change from record to record, due to lack of synchronisation between input step and ADC clock. This, in conjunction with the principle of equivalent time sampling, enables determination of actual step response of ADC.

Output of the step generator (recorded with a digital oscilloscope) used is shown in Fig. 9 and it has a rise-time of about 2ns. Shorting a DC voltage, via a mercury-wetted relay, to ground, produced the step waveform. The step response of the ADC was estimated from 25 step records (using equivalent time sampling principles), has a rise-time of ~5ns, and is shown in Fig. 10. A 10:1 voltage probe was used to reduce applied voltage to suit input range of RTD 710A.

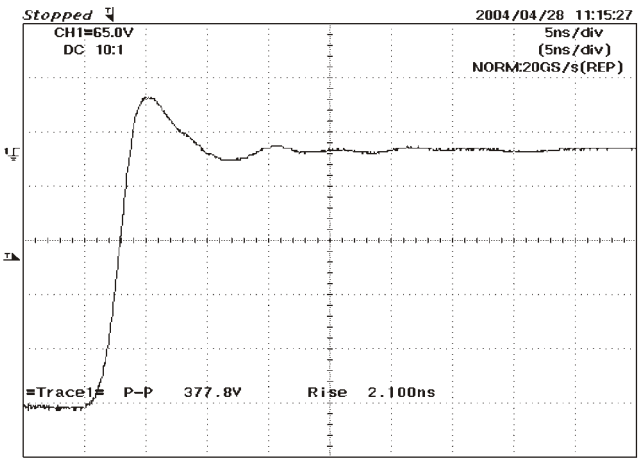

Fig. 9 Signal used for Step Calibration of RTD 710A.

D. *Impulse Calibration*

Impulse calibration is the reference method to establish impulse scale factor of approved impulse waveform recorders. It is also the reference method to check time parameter from the waveform data record. The type and polarity of the calibration impulses shall be that of the impulse to be measured. The output peak and time parameters corresponding to the calibration impulse should be evaluated for at least 10 impulses. Unlike non-linearity tests, the impulse calibration shall be made on each range of use for tests.

TABLE I
IMPULSE CALIBRATION*

No.	Peak (Volts)	T_1 (μs)	T_2 (μs)
1	77.81	0.8134	62.15
2	77.73	0.7970	62.40
3	77.66	0.7992	62.15
4	77.73	0.8097	62.35
5	77.66	0.7933	62.15
6	77.73	0.7989	62.30
7	77.66	0.8139	62.25
8	77.73	0.8024	62.20
9	77.81	0.8036	62.05
10	77.66	0.8195	62.30
Average	**77.72**	**0.805**	**62.23**
Std. Dev.	0.05865	0.00858	0.1085

(*Input = 80V, Shape=LI Short. POL=+Ve, VOL= 4V, CH2, Offset=100%, Length=8K. Sample Interval = 50 ns. Probe attenuation= 10:1).

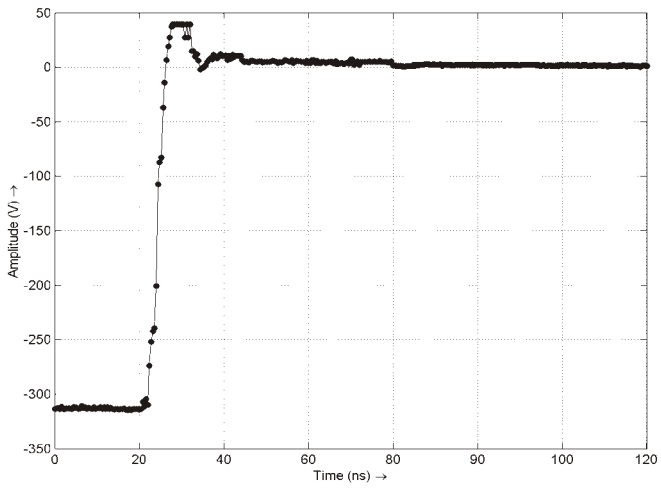

Fig. 10 Step response of RTD 710A reconstructed from multiple (25) step records.

Test set up consists of a programmable, highly precise and calibrated impulse generator (RIC 422), the DUT and the controller. RIC is controlled through the computer and generates a pre-set number of impulses (Short, standard lightning impulse wave of 0.84/60μs) sequentially, with a set delay time. These impulses are applied to the DUT and the responses are stored in a file. The peak value and time parameters are computed. The results are listed Table 1, for 10 impulses. As RIC is directly traceable to international labs (PTB, Germany), this test can be considered as absolute.

IV. IMPLEMENTATION ISSUES

At the outset, the possibility of performing almost all tests on ADCs (as per standards) was demonstrated with available equipment. It turns out that, with an arbitrary waveform generator, most of the tests can be done. However, we must hasten to add that, in reality for each test, the signal sources to be used must be of metrology-class, they be calibrated, be of extremely high-quality and meet the stringent specifications. It is worth to note that the signal source must have a resolution

of at least four times the DUT. Obviously, such sources are expensive. With availability of such sources, it would be possible to test ADCs just like other labs in the world. Although, such quality signal sources might not always be available, tests on digitizers can still be performed with available equipment to ascertain, if there exist any gross errors or not. Specifically, following are the implementation issues one encounters with each of the test, along with the required signal source specifications.

1. In static test, a major problem is the prohibitive time required for high resolution ADCs. Typically, for a 10-bit, it takes ~3 hours. Some efforts and research to reduce this test time are under consideration. DC signal source used must have very low noise level, very low drift, good stability, and possess required minimum amplitude resolution. It must possess external trigger option, as internal trigger will not work for low inputs. A small overdrive is needed to completely span a given range.
2. In all dynamic tests discussed, it is most essential that the signal source should have excellent spectral purity, low noise, high frequency-resolution and frequency-stability, and linearity (for triangular wave histogram test). Also, harmonic distortion must be very low. In beat frequency and FFT test, input must be non-harmonically related to sampling frequency. Also, in FFT test, integral number of cycles of data must be gathered to avoid (windowing and) data truncation effects.
3. A highly precise, stable, programmable and repetitive step generator with low rise-time (a few ns) is required. If any attenuators are used (in most cases needed), its ratio must be accurately known. The step generator output must not possess excessive overshoot, creep, etc, as the RMS law of estimating effective rise-time will not be valid.
4. In an impulse calibrator, a calculable calibrator is used, wherein the impulse being generated is precisely known, both in shape and amplitude. RIC 422 used in this work was one such calibrator. Although they are expensive, standards still specify this test as mandatory.
5. Results of the two ADC systems presented should not be interpreted on absolute terms to assess their performance, as the sources used were not metrology-class and also not calibrated themselves. The intention was to demonstrate ability to perform such tests.
6. Complete access and control of digital data directly from ADC memory (not from files) is an essential pre-requisite for performing some tests. Providing the user this access must be made mandatory. The existing International Standards are silent on this matter.
7. Aperture uncertainty and word-error rate measurements were not done due to non-availability of equipment like precise time-mark generators etc.

V. Conclusions

This paper essentially demonstrates possibility of setting-up and implementing (for the first time in the country) an environment to comprehensively test high-speed and high-resolution ADCs, which are employed in digital impulse waveform recorders. Almost all the test methods described in International Standards IEC 61083-1 and/or IEEE 1057 were implemented successfully, using available equipment/signal sources. It was shown, with an arbitrary waveform generator, how most of the tests could be done. Results for an 8 and 10-bit ADC system (viz. Yokogawa DL 1540 and Tektronix RTD 710A) were presented. In summary, it emerges that once pertinent signal sources complying with the stringent specifications become available, actual calibration can be performed within the country itself.

Lastly, the necessity of a National Standard on testing ADCs is urgently felt, and should be considered immediately. It must be mentioned here that, the users, while trying to implement tests following IEC or IEEE Standards, face certain difficulties and ambiguities. In some cases, tests cannot be performed at the user end, thus, compelling him to approach the manufacturer. Therefore, instead of merely declaring the National Standard as a '***dual or equivalent***' of existing international standards, it would prudent, if a standard based on them is evolved, in which, all contentious issues and matters are adequately addressed and resolved. It is believed that, the requisite expertise and experience for undertaking such a task is available in the country.

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