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PERFORMANCE ANALYSIS OF A FAST DIGITAL INTEGRATOR FOR MAGNETIC FIELD MEASUREMENTS AT CERN

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Abstract: A Fast Digital Integrator (FDI) has been designed at CERN for increasing performance of state-of-art instruments analyzing superconducting magnets in particle accelerators. In particular, in flux measurement, a bandwidth up to 50-100 kHz and an accuracy of 10 ppm has to be targeted. In this paper, basic concepts and architecture of the developed FDI are highlighted. Numerical metrological analysis of the instrument performance is shown, by focusing both on deterministic errors and on uncertainty in time and amplitude domains.

Keywords: Magnetic Materials/Magnetics, Particle Accelerator Science & Technology/Nuclear and Plasma Sciences, Signal Analysis/Signal Processing.

1. INTRODUCTION

One of most suitable techniques for testing superconducting magnets accurately is based on rotating coils [1]-[2]: the output signal of a calibrated coil, turning inside the magnet, is proportional to the derivative of the magnetic flux. The coil signal is integrated digitally in the angular domain, by exploiting the output pulses of an encoder mounted on the shaft of the coil. A flux sample is released at each encoder pulse. With this aim, the PDI, Portable Digital Integrator, has been used at CERN and over the world in most important subnuclear laboratories [3]-[6]. It is based on a voltage-to-frequency converter and its dynamic metrological performance is strictly related to the Over-Sampling Ratio (OSR) and to noise shaping.

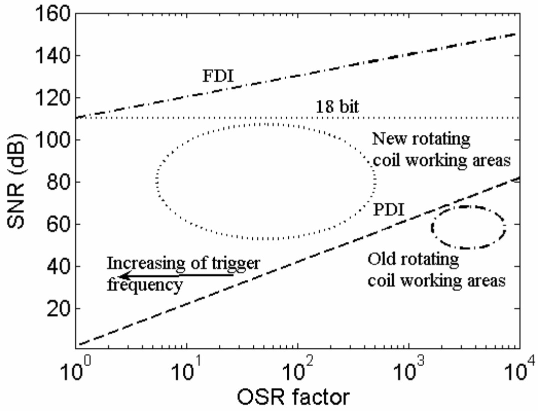

Fig. 1.-PDI and FDI theoretical performance.

For more demanding applications, such as qualifying magnets of Large Hadron Collider at CERN [7], dynamic effects can be figured it out correctly only if the flux is analyzed over a bandwidth of 50-100 kHz, with an accuracy of around 10 ppm [8]-[9]. Thus, a new generation of faster and more accurate rotating coils has been developed [1]-[2]. In Fig. 1, the working areas of old and new generations of rotating coils are compared: the new ones lead to an increase in trigger frequency, i.e., in the flux sampling rate. This causes a decrease in OSR, and, correspondingly, in PDI performance. This new hard measurement goal demands for high-accuracy both in time and in amplitude domains.

At SACLAY, a PXI acquisition board, hosting numerical integration of voltage samples, was developed [8]. A patent-protected concept guarantees time uncertainty to be reduced by a time-stamp resolution within 5 ns. However, the voltage is quantized by a 16-bit ADC. At FERMILAB, an ADC-DSP chain is exploited [9]. However, the method was validated at conceptual level on two VME boards, and resulted only 5 times faster than PDI. Moreover, offset and gain errors on the measuring chain requires repeated corrections and adjustment to a skilled operator. In synthesis, state-of-the-art proposals, [8]-[12], do not allow the abovementioned requirements to be satisfied fully at operating level [8].

AT CERN, under the framework of a cooperation with University of Sannio, a Fast Digital Integrator (FDI) for overperfoming PDI and current state-of-the-art solutions, as well as satisfying new rotating coils requirements, has been developed. In the following, in Section 2, the conceptual architecture of the FDI is recalled; in Section 3, main uncertainty sources are highlighted, and, in Section 4, the FDI performance is investigated numerically by analyzing deterministic errors, and uncertainty in time and amplitude domains.

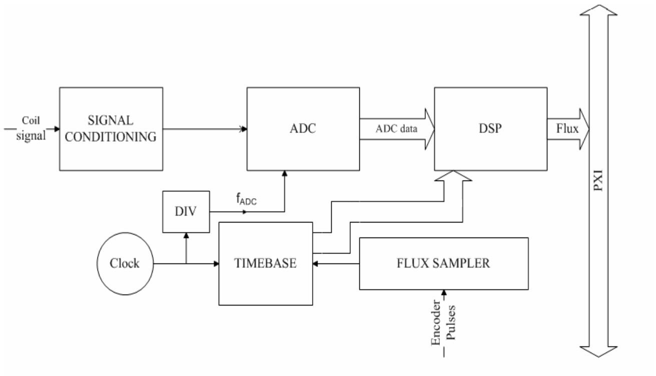

Fig. 2. – FDI architecture.

2. THE FDI PROPOSAL

Without benefiting of noise shaping (no feedback is applied), the FDI keeps the advantage of a large oversampling (OSR ranging from 8 up to 800) and a high-resolution digitization (18 bits, Fig. 1).

The FDI architecture (Fig. 2) is based on the digital conversion and the numerical integration of the coil signal. The input signal is conditioned by a low-noise custom Programmable Gain Amplifier, PGA, providing an automatic calibration and correction of gain and offset errors [13]. The digital conversion is carried out by a 18-bit ADC, with a maximum sampling rate of 800 kS/s. Digital data are then handled by a Digital Signal Processor, DSP, for running on-line numerical integration and other suitable algorithms for performance improvement. The trigger events, i.e. the encoder pulses, coming out from the flux sampler, are measured by a time-base with a resolution of 50 ns. This allows the flux to be evaluated in the angular domain suitably. Owing to a DSP-based on-line integration, an increase in the flux sampling rate, in order to enlarge the input signal bandwidth, does not impact on the FDI performance directly. Theoretically, flux sampling rate can increase until the value of the ADC sampling rate, without loosing the 18-bit resolution on the voltage signal, guaranteed by the ADC. Thus, as greater the OSR, as better the FDI performance is.

3. UNCERTAINTY SOURCES

Conceptually, the basic idea of the proposed instrument allows the new challenges for magnetic measurements to be faced up. However, in the practice, timebase, PGA, and ADC must exhibit an adequate accuracy level in order to satisfy the new requirements.

In case of rectangular algorithm, the *k-th* magnetic flux sample between two trigger pulses (Fig. 3) is evaluated as:

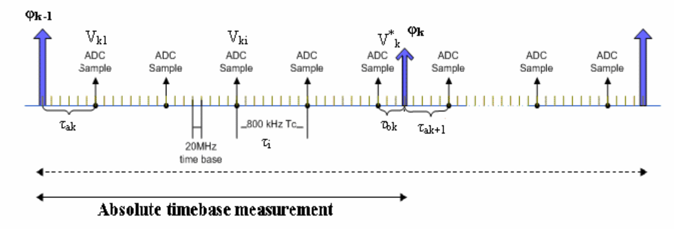

Fig. 3. – Trigger time measurement by an absolute timebase.

Table 1. Flux uncertainty arising from amplitude domain.

Source	SNR input	ENOB	Accuracy (σ)
Quantization	110 dB	18	$\pm$ 2.7 *10^{-8} Vs
Nonideal Acquisition	100 dB	16	$\pm$ 3.0*10^{-7} Vs
	80 dB	13	$\pm$ 3.0*10^{-6} Vs

$$\varphi_k = \tau_{ak} V_{k1} + \sum_{i=1}^{N-1} V_i \tau_{ADC} + \tau_{bk} V_k^* \qquad (1)$$

where τ_{ak} is the time between the *k-1-th* trigger pulse and the next ADC sample, V_{k1} is the first ADC sample after the *k-1-th* trigger pulse, N is the number of samples acquired between two trigger pulses, V_i are the voltage samples, τ_{ADC} is the ADC sampling period, τ_{bk} is the time interval between the *k-th* trigger pulse and the previous ADC sample, , and V_k^* is the voltage sample at the trigger event, evaluated by means of interpolation.

The flux depends on the voltage signal V_i and the time resolution, τ_{ADC}, given by the ADC sampling period. The trigger event is recognized by the timebase within a resolution of 50 ns in order to calculate τ_{ak} and τ_{bk} (Fig. 3). The timebase allows the time domain and the angular domain to be linked finely in order to evaluate the flux adequately.

In the time domain, main uncertainty sources arise from (i) the ADC sampling jitter, (ii) the encoder, (iii) the flux timebase resolution, and (iv) the flux timebase jitter. The ADC sampling jitter can be considered as negligible, being in the order of a few of nanoseconds. The encoder uncertainty is reduced to the timebase resolution, i.e. 50 ns. Thus, in the following, the analysis will be focused on the uncertainty sources (iii) and (iv).

In the amplitude domain, main uncertainty sources arise from (i) the analog front-end, and (ii) the signal digitization. Moreover, the on-line numerical evaluation of the voltage integral will cause a deterministic error, depending on the algorithm and on the minimum time step.

In Table 1, as an example of the impact of uncertainties in the amplitude domain, the flux uncertainty is shown for several values of input SNR. For the first case, only the ADC quantization noise was considered (uniform noise); for the last two cases, the possible uncertainty sources of the analog front-end were considered too. In particular, the front-end uncertainty was modeled by a Gaussian distribution according to central limit theorem.

4. FDI PERFORMANCE ANALYSIS

The FDI expected performance was analyzed by a numerical simulation. In such an analysis, the error was evaluated as difference between the analytical and the numerical integral, at varying (i) the integration algorithm, (ii) the sampling rate, (iii) the trigger frequency, (iv) the timebase measure, (v) the timebase jitter, and (vi) the noise in acquisition chain. As input signal, a sine wave with a peak-to-peak level of 2.0 V_{pp}, and a frequency of 10 Hz was considered.

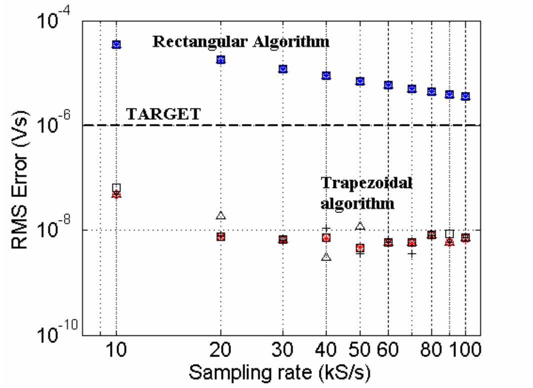

Fig. 4. – Sampling rate, trigger frequency, and algorithm influence on FDI performance (trigger frequency ranging from 256 Hz to 4096 Hz).

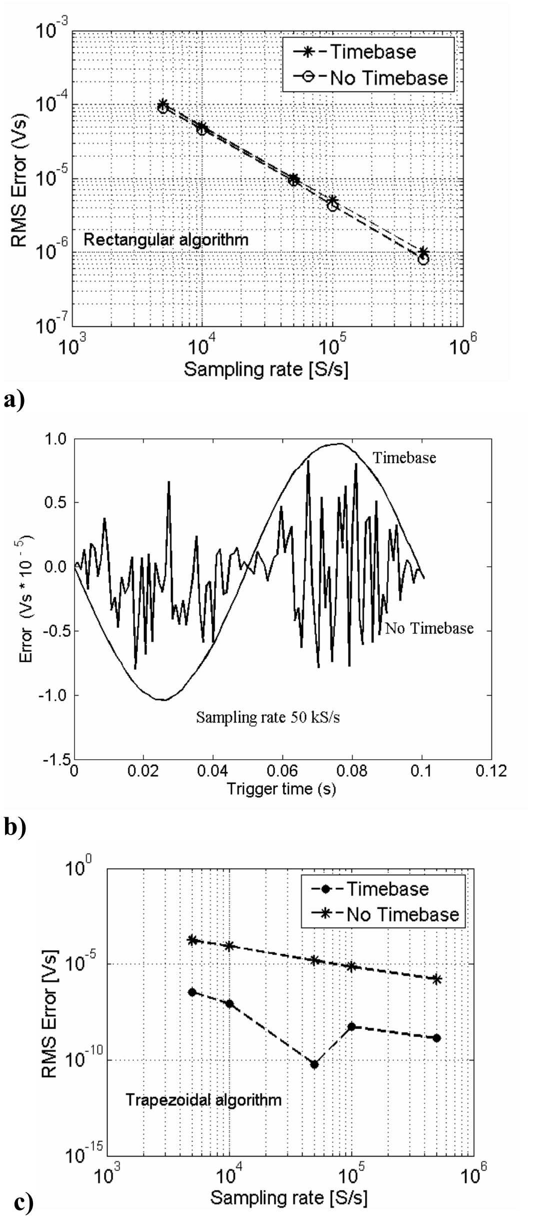

Fig. 5. – Timebase influence on FDI performance: RMS error for (a) rectangular algorithm, (b) (particular), and (c) trapezoidal algorithm.

In the following, the analysis of (i) *deterministic errors*, (ii) *time domain uncertainty*, and (iii) *amplitude domain uncertainty* is illustrated.

4.1. Deterministic Errors

In Fig. 4, the RMS error of the simulated FDI is plotted as function of the ADC sampling rate, for different trigger frequencies (points with different symbols), and for two numerical integration algorithms (rectangular and trapezoidal). In these conditions, the trigger frequency does not affect the FDI performance. It is worth to note that the trapezoidal algorithm, implemented as a first-order on-line filter, already gives rise to an error less than to 10^{-6} Vs.

Without timebase, the trigger event detection is based on the ADC sampling period. The impact on FDI performance of a timebase at 50 ns is shown in Fig. 5. In case of rectangular algorithm, the RMS error is about the same with and without the timebase (Fig. 5a). The lower accuracy of time measurement, provided by the ADC sampling period, acts as a dither effect on the numerical error of the rectangular method (Fig. 5b). In case of trapezoidal algorithm, timebase advantage is evident (Fig. 5c): performance is improved of about three orders of magnitude.

4.2. Time Domain Uncertainty

In this section, the effects of timebase rounding, timebase jitter, and noise in the acquisition chain are analyzed.

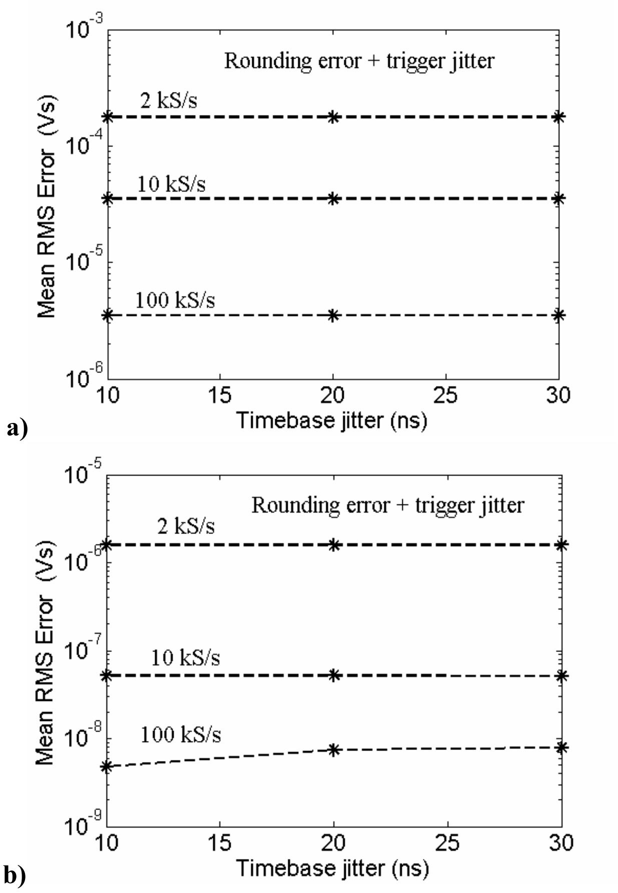

Fig. 6. – Timebase uncertainty influence on the deterministic flux error: (a) rectangular and (b) trapezoidal algorithms.

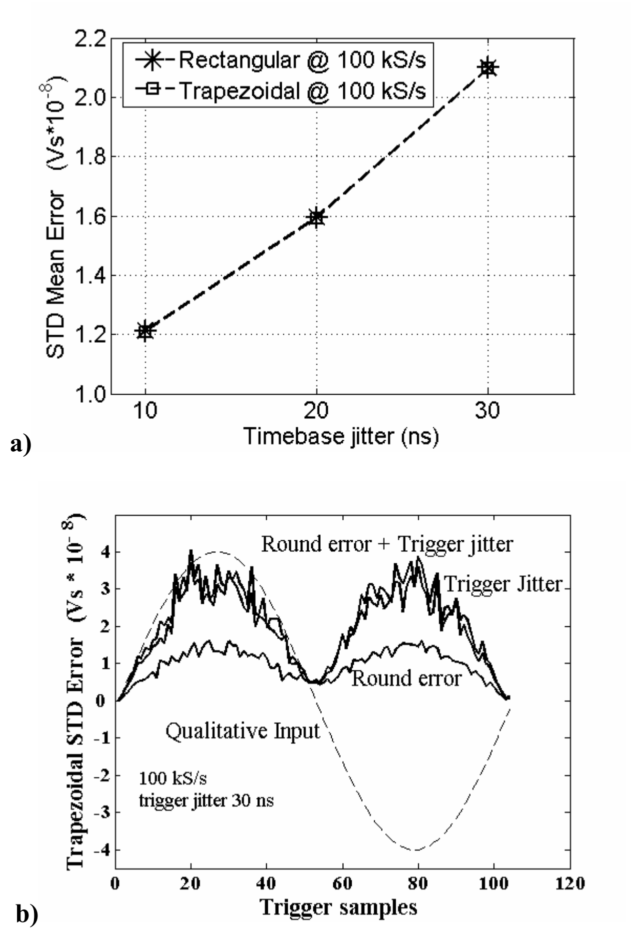

Fig. 7. – Time-domain uncertainty influence on the flux: (a) random error, and (b) random error time waveforms.

Timebase at 50 ns produces a related rounding error in the detection of the trigger event and can exhibit a significant jitter too. In Fig. 6, the mean of the RMS error, evaluated over 50 experiments is plotted as function of the timebase jitter, in presence of rounding error, for different sampling rate, and for (a) rectangular and (b) trapezoidal algorithms. This uncertainty source impacts on the deterministic error only for the trapezoidal method (Fig. 6b) and for a sampling rate not less than 100 kS/s.

The uncertainty, evaluated as the standard deviation of the mean error over 50 experiments, increases as function of the timebase jitter (Fig. 7a) and it is independent on the numerical algorithm that affects only the deterministic error. The uncertainty on the flux in time domain follows the absolute amplitude of the input signal, and does not increase with time measurement, owing to the absolute timebase measurement (Fig. 7b).

4.3. *Amplitude Domain Uncertainty*

In this section, the effects of the uncertainty arising from analog front-end and from digital conversion are analyzed.

Such uncertainty sources were simulated as a Gaussian noise added to the input signal. The uncertainty on the flux does not depend on the numerical method. Such as expected from theory, it increases according to the square root of the number of samples (Fig. 8a). Thus, it increases with the time, and it is a linear function of the voltage signal uncertainty (Fig. 8b).

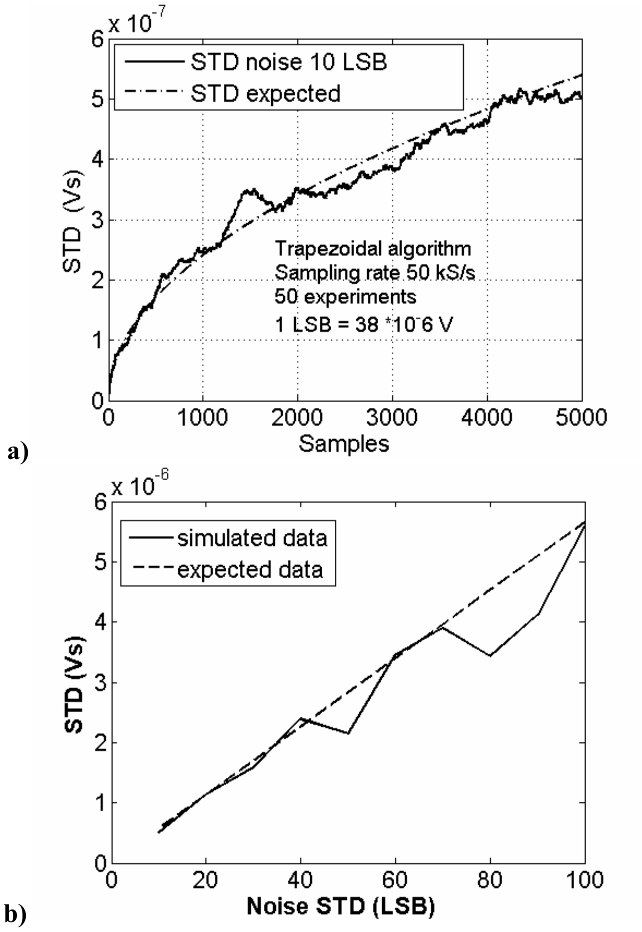

Fig. 8. – Time-domain uncertainty influence on the flux random error as function of: (a) the time and (b) the input noise for a fixed number of samples (5000), 1 LSB= 38 μV.

For the rectangular algorithm, the deterministic error on the flux is dominated by the numerical error and the noise effect is not evident (Fig. 9a). Conversely, in the case of the trapezoidal algorithm (Fig. 9b), the flux error depends on the amplitude domain uncertainty. For a Gaussian noise, with a standard deviation of 20 LSB (760 μV), the flux error is below the target (10^{-6} Vs).

The numerical integration of the input signal, by means of trapezium, provides a first-order filter. Performance can be improved by applying higher-order filters [14]-[16]. However, to design the filter properly, a further understanding of the coil noise is needed.

5. CONCLUSIONS

The basic idea of the FDI, with a high-OSR, high-resolution digital conversion, and a numerical integration allows the new requirements for magnetic measurements for particle accelerators to be satisfied. The time measurement with a resolution of 50 ns improves the FDI performance, by increasing the accuracy of the passage from time to angular domains.

In further work, suitable algorithms can be applied by means of the DSP to reduce the noise effect. Then, the coil

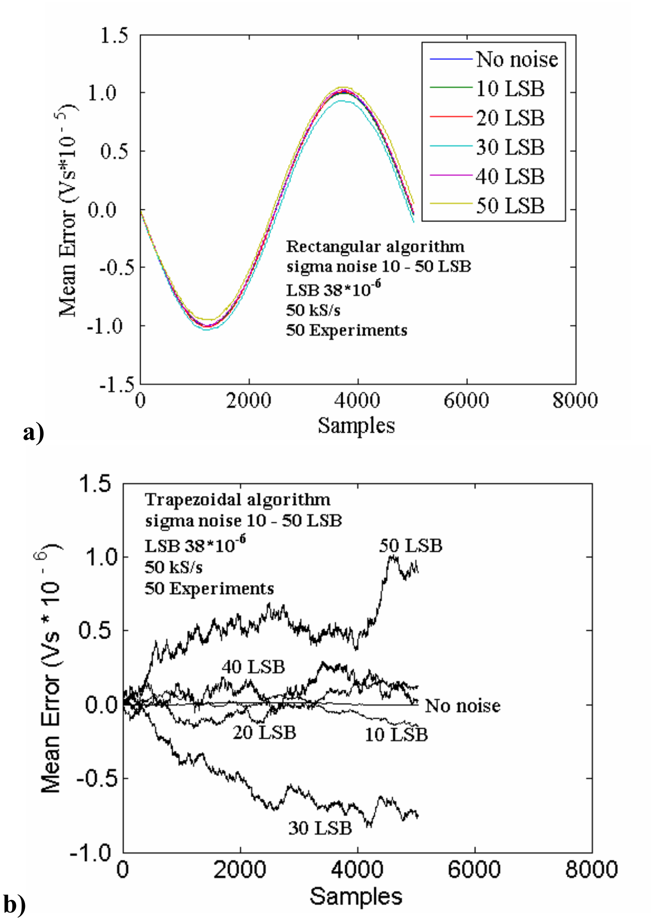

Fig. 9. - Voltage signal uncertainty influence on the flux deterministic error for (a) rectangular and (b) trapezoidal algorithms.

signal will be analyzed in order to better understand its features. Finally, a metrological characterization of the analog front-end on the second prototype will be carried out to in order to go deeper inside the noise uncertainty sources.

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