

A Data Reduction Algorithm for Magnetic Measurement Pre-processing at CERN

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Abstract- The principle of a data reduction algorithm, based on real-time adaptive sampling, specifically optimized for high-rate automatic measurement systems, is proposed. An adaptive sampling rule based on power estimation allows the optimum amount of information to be gathered in real time. The sampling rate is adapted when the limit conditions of insufficient/redundant information for the required signal processing is achieved. The tracking condition is defined by the reference power level in the Nyquist band necessary to the required post-processing procedure. Preliminary experimental results of the application to an automatic measurement system for testing superconducting magnets at the European Organization for Nuclear Research are reported.

I. Introduction

At the European Organization for Nuclear Research (CERN), the design and realization of the particle accelerator Large Hadron Collider (LHC), the largest machine ever built by the human kind, required a remarkable technological effort in many areas of engineering. In particular, the tests of LHC superconducting magnets disclosed new horizons for magnetic measurements [1]. A new generation of fast transducers [2]-[3], capable of increasing by two orders the bandwidth of harmonic measurements (10 to 100 Hz), when compared to standard techniques (typically 1 Hz or less), and still maintaining a typical resolution of 10 ppm, have been developed. Moreover, also a Fast Digital Integrator (FDI), reducing on-line flux analysis time down to 4.00 μ s, within a resolution of 50 ns, was prototyped and on-field tested successfully [4]. The higher sampling rate of such a measurement setup produces a large amount of data by giving rise to an exponential increase in data storage requirements. Thus, new tools for measurement optimization are needed in order to decrease the size of measurement results by controlling the quality loss simultaneously.

Data reduction techniques achieve from a measurement process the minimum amount of information sufficient to any kind of further analysis [5]. Different techniques for data reduction and measurement optimization have been proposed [5]-[10]. In particular, in biomedical applications, adaptive sampling algorithms are widely used to reduce data size, while preserving clinical acceptability of the reconstructed signal [5]. In the development of sensor networks for environmental monitoring, the distributed structure of the measurement system led to decentralized autonomous cooperative intelligent sensors, capable of minimizing resource consumption (energy and network bandwidth), by adapting their sampling rates to the actual environmental conditions [6]-[8]. Anyway, in both these fields, applications have been so far developed only for measurements with low sampling rates (typically below 100 S/s). Furthermore, some of the proposed methods turn out to be highly complex, by requiring: a model of the measurand physical process [6], the design of a compound Kalman filter [7], the solution of a constrained optimization problem [8]. Their computational burden limits their use for fast real-time data reduction up to tens of samples per second. Other techniques, such as histogram equalization [9] and entropy-based adaptive sampling [10], were proposed for image processing applications. However, these methods include a phase of data analysis needing for the availability of the data set as a whole, thus preventing their use for fast real-time applications.

In this paper, a batch real-time data reduction algorithm based on adaptive sampling, specifically optimized for high-rate magnetic measurements, is presented. Data reduction is achieved by re-configuring the instruments in real time during the measurement task execution. Preliminary

experimental results obtained at CERN on a test bench for automatic measurements on superconducting magnets are presented.

II. Proposal

In the following, (i) the *basic ideas*, (ii) the *strategy*, and (iii) the *procedure* of the proposed algorithm are illustrated.

A. Basic ideas

According to the fundamental data reduction principle of gathering only the minimum amount of information sufficient to any kind of further analysis, a rule for adapting the sampling by tracking the signal power in the Nyquist band is defined.

The sampling rate is adapted in real time when a limit condition is approached. The limit condition is based on the Shannon-Nyquist theorem in terms of the sampling rate defining the Nyquist bandwidth including the minimum power necessary to capture the required features of the signal.

The corresponding algorithm is based on the estimation of the power in a frequency band whose upper limit is the Nyquist frequency, and on the comparison with thresholds representing the power level in the band for which the current sampling rate is considered adequate. The sampling rate is increased/decreased when relatively high-frequency terms are present/absent into the power estimator.

B. Strategy

If the sampling rate is f_s , the power estimator is unable to adequately treat a signal whose frequency approaches $f_s/2$. Moreover, if the sampling rate is only f_s , the presence of signals with frequency greater than $f_s/2$ can not be revealed. However, an increase of the estimated power in the observed frequency band $[f_0, f_s/2]$, with $f_0 < f_s/2$ to be suitably chosen, at a level above a suitable threshold, can reveal the presence of higher frequency components approaching the limit of the current observable band. Therefore, an increase in resolvable frequencies can be obtained by triggering an increase in the sampling rate. Likewise, the absence of large terms in the band $[f_0, f_s/2]$ is used to trigger a decrease in the sampling rate. In this way, error penalties incurred by slightly reducing the sampling rate in places where the signal is relatively uninteresting are not likely to be high.

This is true if the variation of the power content of the signal can be considered stationary with respect to the algorithm adaptation time. The frequency f_0 is to be chosen as a function of f_s , thus both the extremes of the observed frequency band can vary while the sampling rate is adapted.

C. Procedure

The proposed algorithm can be summarized in the following steps (Fig. 1):

1. acquire the batch of samples at the current rate f_s ;
2. estimate the signal power in the frequency band $[f_0, f_s/2]$;
3. compare the estimated power to the threshold, and if necessary update f_s ;
4. if more data are incoming go to point 1, else exit.

The algorithm is modular and generic: different techniques can be used for power estimation, thresholds computation, and sampling rate updating.

III. Experimental results

The proof of the principle and the performance of the proposed algorithm was carried out at CERN by implementing an experimental demonstrator. Preliminary tests were performed on a measurement station based on rotating coils [11], one of most accurate technique for superconducting magnet testing (Fig. 2). In the following, (i) the *experimental case study*, (ii) the *algorithm design*, and (iii) the *preliminary data reduction results* are illustrated and discussed.

A. Experimental case study

In the rotating coils test technique (Fig. 2) [11], a coil turns in the magnet under test and its output signal is proportional to the flux derivative, according to Faraday's law. The coil signal is integrated in the angular domain by means of the output pulses of an encoder mounted on the rotating coil shaft. A

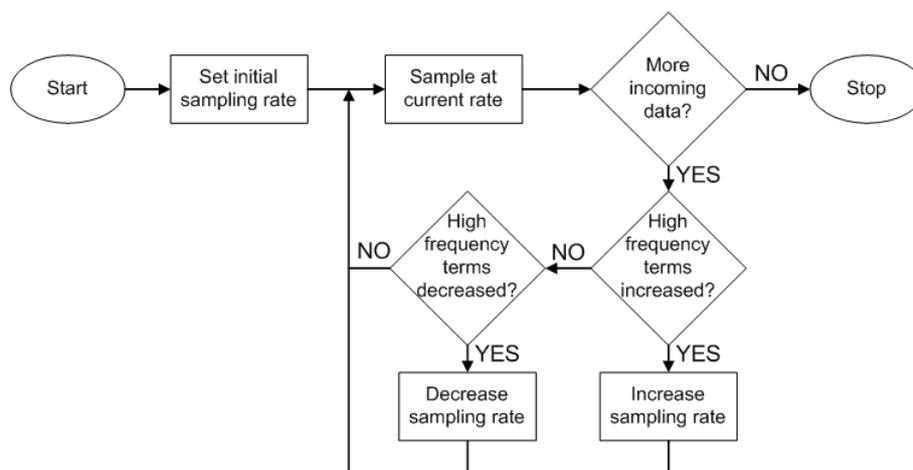


Figure 1. Flow chart of the proposed algorithm.

Fourier analysis of the flux finally yields the multipoles of the magnetic field generated by the magnet under test.

On this basis, a test bench (Fig. 3) was assembled with:

- a motor controller MAXON EPOS 24, accessible through RS232, for handling the motor turning the coil inside a superconducting magnet at a constant rotation rate;
- a Fast Digital Integrator (FDI), a CERN-University of Sannio proprietary PXI general-purpose digitalization board, configured for the coil signal acquisition and numerical integration [4];
- an encoder board: a CERN proprietary PXI board, for managing the encoder pulses and feeding the trigger input of the FDI;
- a superconducting magnet at cryogenic temperature (1.9 K) used as *unit under test*, supplied with a current of 1500 A to generate the magnetic field;
- a software developed by means of the Flexible Framework for Magnetic Measurements (FFMM) [12].

B. Algorithm design

For the above case study, the proposed algorithm was designed by determining: (i) the application level of the data reduction, (ii) the technique for power estimation, (iii) the thresholds computation, and (iv) the sampling rate updating.

Application level of the data reduction. In an automatic test system, data reduction techniques can be applied at level of *instrument firmware*, *instrument software*, and *station software*. At level of the *instrument firmware*, reduction acts on the device directly, thus reducing the data amount on the interface bus. Furthermore, an adaptive parametric management of the measurement process in real-time exploiting the computing capabilities of intelligent devices makes autonomous the instrument. However, the access to the internal instrument code and programming is needed. At level of the *instrument software*, the reduction is achieved by a centralized computing unit. The adaptive management implies a higher adaptation time, therefore, the risk of losing some information when sudden or unpredictable variations arise is to be faced. At the level of *station software*, generally the sampling rate is not adapted. Data acquired at high sampling rate are temporarily stored in a buffer, analysed and reduced before being definitively saved. The risk of losing some information is strongly reduced, but no optimization of the amount of data transferred through the bus is achieved.

For these reasons, in the algorithm design for the above case study on magnetic measurements, the proposed reduction algorithm was applied at instrument software level.

Technique for power estimation. The power of the signal was computed through a Fourier analysis, namely by means of the Fast Fourier Transform. The algorithm

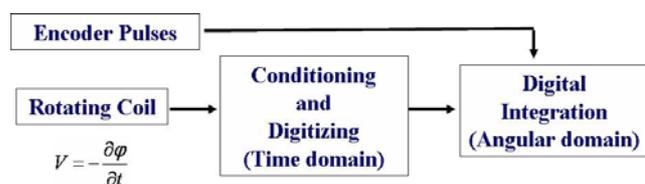


Figure 2. Rotating coil measurement principle.



Figure. 3. The superconducting magnet test bench at CERN.

updates the estimation of the signal power after a batch of samples of fixed size is acquired.
Sampling rate updating. The width of the frequency range considered for the power estimation was chosen equal to one fourth of the resolvable bandwidth. Thus, when a power increase is detected, the algorithm is likely to have enough time to increase the sampling rate before important signal features exit the current observable bandwidth. A suitable trade-off between reaction time of the algorithm to signal variations and computational burden was joined according to the specific application constraints.
Thresholds computation. The threshold terms were determined on the basis of the noise level expected in the observed frequency range. In particular, upper and lower limits on the power admissible in the observed frequency range were defined, in order to trigger the increase/decrease of the sampling rate, respectively.

C. Preliminary data reduction results

The proposed data reduction algorithm was implemented preliminarily in MATLAB[®] and applied to measurement results of the above described demo bench. The algorithm was then executed in order to find the optimal sampling frequency at which the measurement could be performed, therefore the signal was consequently reduced and saved. Afterwards, the multipole expansion of the magnetic field was determined by means of a suitable analysis process [13].

The procedure was repeated for different settings of the algorithm, corresponding to different optimal sampling rates and consequently to different compression ratios.

As an example, the results with 128 points per turn acquired from a coil rotating at a speed of 8 rps are shown in Tab. I. The flux samples were acquired at the sampling rate of 1024 S/s. The compression ratios (the size of the original data divided by the size of the reduced data), and the RMS error on the

Tab. I. Compression ratio and RMS error for the proposed and a literature algorithm.

Original Signal	131072 points, 1024 S/s			
Reduced Signal	Optimal Sampling Rate (S/s)	Compression Ratio	RMS Error (% UNITS)*	
			Prop. alg.	Fan alg. [14]
	512	2	0.189	0.799
	256	4	0.315	3.070
128	8	38.261	72.452	

* harmonics up to the 10th are considered

multipoles estimation with respect to the original signal, used as reference, are also provided. Harmonics of the magnetic field up to order 10 were considered. They are normalized with respect to the main field component and multiplied by a factor 10^6 (percentage “units” [13]). These preliminary results highlight how the algorithm is capable of achieving a remarkable trade off between reduction ratio and fidelity of the reconstructed signal.

For the sake of the comparison, the RMS error on the multipole expansion obtained from the reduction of the same measurement data by means of a classic adaptive sampling method, the Fan algorithm [14], are also reported in Tab. I for different compression ratios. For similar ratios, the comparison shows a remarkable reduction of the error when the new algorithm is employed. In particular, with a compression ratio of 4 it is still able to provide an estimation of the field harmonics with an RMS error of a few tenths of percentage units.

IV. Conclusions

In this paper, a batch algorithm for data reduction through adaptive sampling has been proposed. It is fast, reliable, cost effective and can be implemented in real-time in order to extract significant points from a sampled signal, with an information loss within an error range specified by the user through a threshold mechanism.

Preliminary experimental results on magnetic measurements performed at CERN through the rotating coils technique proved the effectiveness of the algorithm. Anyway, these results will be further investigated by implementing the algorithm inside the measurement station in order to verify actual real-time performance, both for rotating coils and for other magnetic measurement applications. In addition, a more comprehensive analysis will be carried out also for the estimation of the magnetic field multipole expansion through rotating coils measurements. Finally, other and more advanced techniques for the detection of high-frequency terms will be considered for the implementation of the adaptive mechanism.

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