XVIII IMEKO WORLD CONGRESS
Metrology for a Sustainable Development
September, 17 – 22, 2006, Rio de Janeiro, Brazil

PARAMETER DESIGN FOR METROLOGICAL CHARACTERISTICS IMPROVEMENT OF A FAST DIGITAL INTEGRATOR AT CERN

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Abstract: The reduction of uncertainty in measurement systems is usually obtained through the use of more accurate components. In this paper, this problem is faced by a statistical parameter design procedure. The proposed method is shown to be effective to improve the metrological characteristics of a Fast Digital Integrator developed at European Centre of Nuclear Research.

Keywords: Uncertainty reduction, parameter design, fast digital integrator.

1. INTRODUCTION

In the design of engineering systems, the variance of the quality characteristic is usually reduced by a cost increase (*tolerance design*) [1]-[2]: higher-quality components are selected, and narrower variations to influence parameters are imposed. A quite different approach has been proposed in control system design (*robust control*) [1]-[4], in electronic circuit design (*tolerance and sensitivity analysis*) [5], or in advanced quality engineering (*parameter design and robust design* [1]-[7]): the system output is made as much insensitive as possible both to influence parameters and to component tolerances by selecting a suitable system configuration. This is usually carried out through analysis techniques of system theory, range methods, or statistical experiment design [1]-[8]. All these techniques adopt a different strategy for the same aim of identifying different nominal values of system components or, more in general, of design parameters, and, thus, do not involve any cost increase in the system. This approach has been applied also to the design of measurement systems [3]-[5]: the configuration capable of minimizing the difference between actual and ideal output, and, simultaneously, maximizing the sensitivity of the measurement system, is selected through parametric optimization techniques by a deterministic approach of control theory. However, the main problem in measurement system design is related to the random variability of the output, i.e. to the measurement uncertainty. Thus, in the design of a measurement system, a deterministic approach turns out to be misleading.

In this paper, an alternative statistical approach to uncertainty reduction, as well as to other metrological performance improvement, in measurement system design is proposed. At first, the idea of statistical parameter design of measurement systems is advanced. On this basis, a procedure of uncertainty reduction, as well as of optimization of metrological characteristics, in the input range as a whole is proposed and applied to a Fast Digital Integrator (FDI) in development at European Centre of Nuclear Research (CERN) in cooperation with Universita' del Sannio.

2. THE PROPOSED METHOD

The parameter diagram of a generic measurement system is shown in Fig. 1 [1], [3]-[5]; where c_i (i = 1, 2,..., n) is a set of control parameters, X_j (j = 1, 2,..., m) is a set of noise factors, and y_k (k = 1, 2,..., p) is a set of output performance parameters. Let us suppose that every c_i could assume q different levels (q = *1, 2, ..., z*). The problem is to find the combinations of c_{iq} that maximize performance $y_{k\text{-}th}$. This task could be faced succesfully by statistical techniques of parameter design [1]-[7]; this approach is suitable everytime the analytical relationships between input and output parameters of a system is unknown [1].
In the following, (i) the *problem description*, and (ii) the *optimization method* are highlighted.

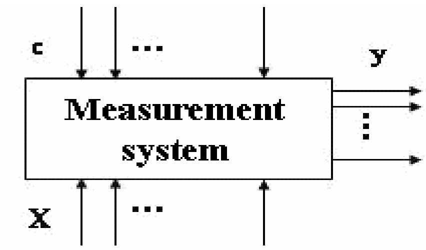

Figure. 1 - Parameter diagram of a generic measurement system.

2.1. Problem Description

In the *a-posteriori* approach of the statistical parameter design, the relationships between control and performance parameters could be obtained by analysing the results of n_p tests:

$$n_p = \prod_i n_{li}^{\,n_{fi}}\,, \tag{1}$$

where n_{fi} represents the i-th parameters group size having n_{li} levels; e.g., for a set of 4 parameters with 3 levels with a repetition number of 5 for each test, 405 experiments have to be done. The burden of this task is reduced by *experimental fractional factorial* plans [1], [3]-[5]. The experimental plan is represented by a matrix (*matrix of experiments*): each row corresponds to an experiment in a given configuration, and each column to a combination of levels of a configuration parameter. The plan is selected among standard ones or designed as proposed in the literature [1]-[8], on the basis of the number of configurations to be experimented, and the eventual need to study specific interactions among parameters.

In the proposed method, an "orthogonal" plan (orthogonal array) was selected [1], [3]-[5]: the columns represent an orthonormal basis of the combinatorial space of the parameter levels.

2.2. Optimization Method

The first step is to choose a suitable objective function, η. The relationship between η and the configuration parameters c_i can be expressed by the following model [1]-[6]:

$$\eta = \mu + \sum_{i=1}^{n} \delta_{iq} + \varepsilon \qquad (2)$$

where μ is the overall mean that is the mean value of η for the experimental plan, δ_{iq} is the deviation from μ due to c_{iq}, and ε stands for the error [1].

Experimental results are then analysed by means of [1]**:** (i) analysis of mean (ANOM)**,** in order to estimate the effects of the configuration options on the optimum attainment; and (ii) analysis of variance (ANOVA) [3]-[5], in order to evaluate the relative weight of such options with reference to the uncertainty of the estimate, and to select only the most significant ones.

ANOM

The value of the average of η obtained in N ortogonal array experiments is estimated by the relation [3]-[5]:

$$\mu = \frac{1}{N} \sum_{j=1}^{N} \eta_j \qquad (3)$$

and the mean m_{iq}, of the results of n_{iq} orthogonal array experiments with c_i at level q_i:

$$m_{iq} = \frac{1}{n_{iq}} \sum_{j=1}^{n_{iq}} \eta_j \qquad (4)$$

the terms δ_{iq} are estimated starting from equation (2) by minimising the sum of uncertainty squares (least-square method):

$$d_{iq} = m_{iq} - \mu \qquad (5)$$

ANOVA

The sum of squares of η can be expressed as follows:

$$\sum_{j=1}^{N} \eta_j^2 = N \cdot \mu^2 + \sum_{i=1}^{n} \sum_{q=1}^{n_w} \left(n_{iq} \cdot d_{iq}^2 \right) + \sum_{j=1}^{N} \varepsilon_j^2 \qquad (6)$$

where N is the number of rows of the selected ortogonal array. The actual incidence of a configuration parameter c_i on the objective function is computed by evaluating its relative weight referred to the uncertinty of estimate of the "variance ratio" F_i:

$$F_i = \frac{\sigma_i^2}{\sigma_\varepsilon^2} \qquad (7)$$

where σ_ε^2 is the variance of the uncertainty and σ_i^2 is:

$$\sigma_i^2 = \frac{\sum_{q=1}^{n_w} \left(n_{iq} \cdot d_{iq}^2 \right)}{q-1} \qquad (8)$$

3. EXPERIMENTAL RESULTS

The proposed method was applied to the above mentioned FDI developed at CERN, under the framework of a cooperation between Magnetic Tests and Measurement (MTM) Group and the Dipartimento di Ingegneria of University of Sannio. At CERN, Portable Digital Integrators (PDIs), based on gain programmable voltage-to-frequency converters, have been used for 20 years successfully [9]. However, in most advanced applications of test and control for the Large Hadron Collider under construction, more constraining requirements of 10 ppm on integrated voltage measurement for an integration time of 1 s are needed for the measurement of magnetic field based on rotating coils. Other laboratories have proposed full digital solutions [10]-[12], however drawbacks related to timing constraints still

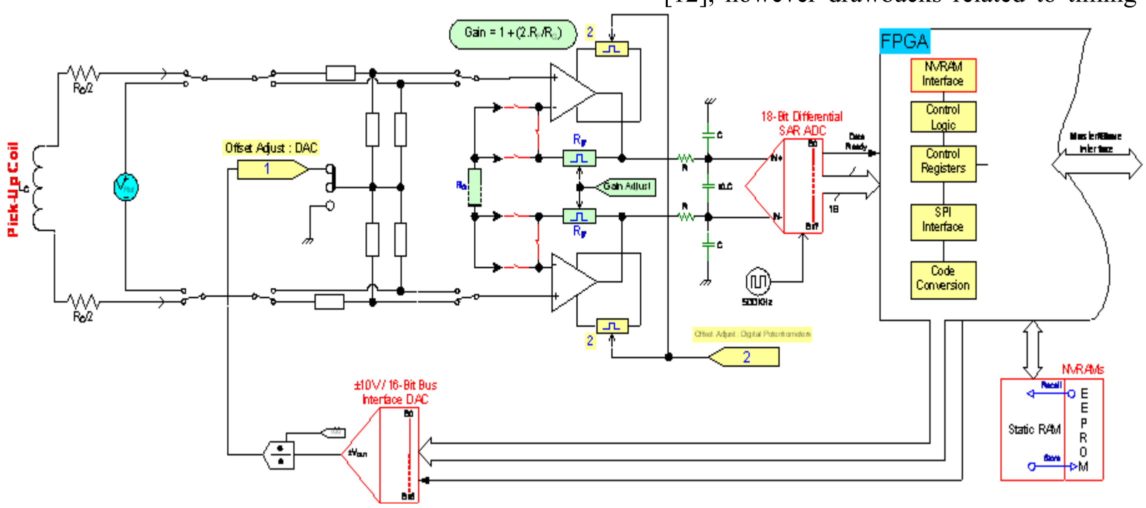

Figure 2. Prototype scheme.

arise.

The main sections of the FDI analog part is shown in Fig. 2:

- the Programmable Gain Amplifier (PGA);
- the 18-bit Analog-to-Digital Converter (ADC);
- the Field Programmable Gate Array (FPGA);
- the digital trimmer for the gain adjustment;
- the Digital-to-Analog Converter (DAC) for the offset compensation.

Tab. 1 – Control parameters with the respective levels

	Parameter	Lev. 1	Lev. 2	Lev. 3
x_1	f_{FPGA} [MHz]	20	35	50
x_2	ADC V_{ref} [V]	4.09	4.096	5.02
x_3	AVDD [V]	4.75	5.00	5.25
x_4	V_{pow}	14.0	14.5	15.0
x_5	R_{gain} [kΩ]	10	11.0	12

Tab. 2 – Experimental Plan L18 (e: empty)

Exp.	x_1	x_2	x_3	x_4	x_5	e	e	e
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

The input signal, picked up form the coil, is conditioned by the PGA and quantized and converted by the ADC; the digital signal is sent to a Digital Signal Processor (DSP) ADSP-21262 through the FPGA Xilinx Spartan III which represents the I/O processor of the FDI. The digital trimmer and the DAC operate in the calibration procedure for a precise adjustment of the selected gain and for the correction of the offset voltage.

The list of the selected control parameters with the respective levels is shown in Tab. 1: f_{FPGA} is the clock frequency of the FPGA; V_{ref} is the external reference voltage of the ADC; AVDD is the ADC analog power input, while V_{pow} is the power voltage fo the instrumentation amplifier of the PGA, and R_{gain} is a resistor that contributes to the final value of $R_{G,}$ the sensing resistor of the PGA (Fig. 2).

There are five parameters with three levels thus the experimental plan L18 [1]-[5] (Tab. 2) was selected.

The chosen objective function was:

$$\eta_f = -10 \cdot \log\left(\sigma_f^2 + \left(\mu_f - 1\right)^2\right) \qquad (8)$$

each experiment (a row of the matrix) was replied n_r = 30 times. In the final paper, the optimal combination of parameters level, carried out with ANOM test; and the terms that have gone over Fisher test on ANOVA for a significancy level of 99 %, will be reported. As well as, the corresponding obtained reduction will be reported.

ACKNOWLEDGMENTS

This work was sponsored by CERN (European Organization for Nuclear Research) trough the agreement No K 120/AT/LHC with the Department of Engineering, University of Sannio, whose supports authors gratefully acknowledge.

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