NMR-SSC Magnetic Field Profiler Applied to Magnetic Field Shimming

H. H. Segnorile, G. O. Forte, G. D. Farrher and E. Anoardo, *Member,* IEEE

***Abstract*— A new methodology aimed to control the spatial dependence of a magnetic field within a volume of interest is described. The designed hardware uses Nuclear Magnetic Resonance (NMR) to sense the magnetic field. A modified version of the Statistical Signal Characterization (SSC) method was used to analyze the NMR signal, providing a dynamical definition of the characterization parameters. The information is used to control the currents driving a set of coils that introduce corrections in the spatial dependence of the main field generated by an independent unit (magnet or electromagnet). As a practical matter, we deal with the particular case of magnetic field shimming.**

***Keywords*— magnetic field, shimming, homogeneity, nuclear magnetic resonance.**

I. INTRODUCTION

THE ABILITY to control the spatial dependence of a static magnetic field, that is, the magnetic field profile, is a required task for a plenty of scientific and technological applications. Due to the relative complexity of the matter and the long times that may be required (mainly depending upon the needed precision), it turns of interest to have effective tools allowing a fast extraction of information about the magnetic field profile. For certain potential application cases, a fast control algorithm is mandatory, see for instance [1-5].

In this paper we are concerned with a new mathematical method for extracting characteristic parameters that define the spatial dependence of a magnetic field, based in an original modification of the Statistical Signal Characterization (SSC) method [6]. The mathematical machinery is used to analyze the envelope of the free induction decay (FID) signal as measured with the aid of an NMR instrument [7]. The method is implemented with an own complete software and hardware system, allowing a quantitative characterization of the magnetic field profile. Compared to other tools like Fast Fourier Transform (FFT) or correlation functions, the method has the basic advantage of allowing a faster analysis due to the use of characteristic parameters that depend of simple mean values of the signals. Therefore, it is adequate for an exhaustive feedback control algorithm and complex implementations.

The key idea of the method is to find a discrimination function f_d sensitive to the desired spatial dependence of the field (for example, the homogeneity in the case of shimming). The magnetic field profile is modified through a set of coils adding a correction to the main field to be controlled. These coils are driven by controllable independent current sources that are adjusted in order to maximize or minimize f_d. The feedback signal used for the control action is the FID NMR signal. The SSC is used to determine the set of statistical parameters from the acquired FID, correlated as much as possible with the desired magnetic field profile. Then, f_d will be a function of these parameters.

For a given magnetic field profile, the FID will have a characteristic envelope, which in turn may also depend upon the NMR sample (that must be selected to avoid spectroscopic structure in the signal). The method is thus based on the cyclic comparison between the signal envelope and a target function representing the desired envelope. Then, f_d should contain information on how far is the estimated enveloped compared to the target.

The general procedure can be resumed in the following steps:

Process the acquired signal.
Extract the target of the acquired signal.
Calculate the statistical parameters.
Calculate f_d.
Modify currents.
Repeat process until f_d achieves the pre-defined value.

II. THE CASE OF SHIMMING

The case of shimming corresponds to a situation where a uniform magnetic field is desired, that is, a highly homogeneous field. Most NMR applications require certain minimum conditions of magnetic field homogeneity. In cases where such requisites are over 10ppm, it is customary to correct the field with a set of shim coils that should be calculated according to the magnetic field geometry. Time dependent corrections are needed when the magnetic field drifts as a consequence of thermal or mechanical stress.

For a phase-sensitive detection of the NMR signal, unless strictly at the on-resonance condition, the FID will have an oscillatory character, modulated in amplitude by a function that contains the desired information. During the magnetic field profiling process, the signal frequency will change and the on-resonance condition may be crossed many times.

H. H. Segnorile, FaMAF, Universidad Nacional de Córdoba and IFEG – CONICET, email: hh.segnorile@conicet.gov.ar

G. O. Forte, FaMAF, Universidad Nacional de Córdoba and IFEG – CONICET, email: forte@famaf.unc.edu.ar

G. D. Farrher, FaMAF, Universidad Nacional de Córdoba and CONICET, email: gfarrher@famaf.unc.edu.ar

E. Anoardo, FaMAF, Universidad Nacional de Córdoba and IFEG – CONICET, email: anoardo@famaf.unc.edu.ar

However, the signal frequency and phase are irrelevant for the case of shimming, since a homogeneous magnetic field will be recognized through a mono-exponential decay envelope of the FID signal.

Since phase detection was used, the signal envelope is extracted through the determination of local extreme points along the signal: the absolute value of those sample points corresponds to the desired envelope (the signal is centered on zero after an offset correction when needed). Note that this procedure requires the signal having an oscillatory behavior, which can be easily achieved by keeping a few kilohertz off-resonance condition, see Fig. 1.

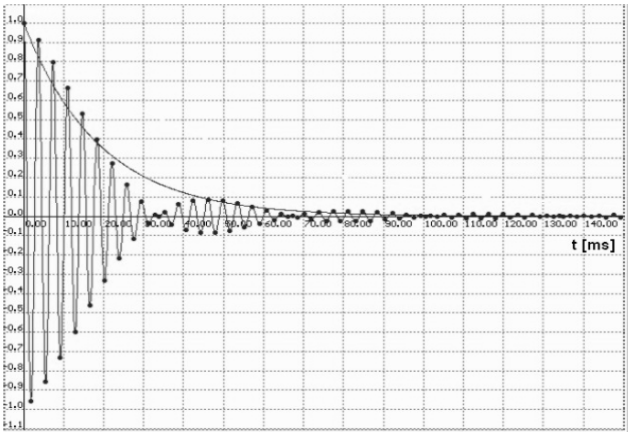

Figure 1. Typical FID signal with a magnetic field inhomogeneous condition after local extreme detection. The monotonic decay represents the best exponential function that fits the absolute values of the extreme points (solid circles).

For a given sample in a perfectly uniform magnetic field, the FID should be a monotonic decreasing function in time, with the longest possible characteristic decay time, which we call T. Since we use a water sample (slightly doped with copper sulfate to adjust the spin-lattice relaxation time), such a monotonic decrease will be assumed to be exponential [8]. In order to calculate f_d, the exponential function that best represents the extreme values of the FID is estimated. The time decay value of that exponential, T_2^*, will be part of f_d. As already mentioned, the rest of the parameters used to calculate f_d must be sensitive to the comparison of the estimated perfect exponential envelope respect to the measured one.

III. MODIFIED STATISTICAL SIGNAL CHARACTERIZATION METHOD

The SSC method [6] allows the characterization of the signal properties in terms of different statistical parameters. The information is extracted from the amplitudes and times of occurrence of the extreme points (local maxima and minima) of the signal. With these values it is possible to define segments of amplitudes $A_n = |a_n - a_{n-1}|$ and periods of time $T_n = |t_n - t_{n-1}|$, being a_n (a_{n-1}) and t_n (t_{n-1}) the ending (beginning) of each segment/period. The standard SSC parameters can be defined as:

$$
\begin{aligned}
M_a &= \sum\nolimits_{n=1}^{N} \frac{A_n}{N},\\
M_t &= \sum\nolimits_{n=1}^{N} \frac{T_n}{N},\\
D_a &= \sum\nolimits_{n=1}^{N} \frac{|A_n - M_a|}{N},\\
D_t &= \sum\nolimits_{n=1}^{N} \frac{|T_n - M_t|}{N},
\end{aligned}
\qquad (1)
$$

being M_a the mean value of the amplitude, M_t the mean value of the period, D_a the mean deviation of the amplitude, D_t mean deviation of the period and N the total number of extreme points. The SSC method is based on the assumption that a few measured parameters are necessary to characterize and discriminate signals originated from a given process. The number of necessary interactions for a successful characterization is proportional to N, which in general results much faster than, for example, the application of Discrete Fourier Transform (DFT, which is proportional to N^2), Fast Fourier Transform (proportional to $N.logN$) or other methods like those based on correlation between functions. Therefore, the SSC methodology is particularly useful for implementations in embedded systems, such as Digital Signal Processors (DSP), or in exhaustive computational events, such as in control of processes, where the size of the algorithm or the speed of execution are important constraints.

In this work we are concerned with the finding of the NMR FID signal whose envelope corresponds to the longest possible exponential decay. However, the FID envelope corresponding to suboptimal magnetic field homogeneity conditions may differ substantially from a pure exponential function (see for instance Fig. 1). Therefore, the application of the SSC method here is twofold: on one hand we want to find the conditions corresponding to the best quality matching between the envelope of our FID signal and the ideal exponential function decay that best represents the acquired data points and, on the other hand, the longest decay signal satisfying the previous condition. Thus, the proposed modified SSC is used to compare the acquired signal envelope with a target exponential function that is estimated from the signal itself after each acquisition. In other words, there is no fixed target function to compare with: each signal has an own target obtained from the estimation of best exponential decay that better represents the acquired data points. The matching comparison consists in calculating the parameters defined in equations (1) for both, the processed acquired signals and the corresponding target.

A fast way to generate the target consists in extracting from the local extreme data set the statistical parameters that characterize an exponential function. These parameters are the characteristic decay time T_2^* and the amplitude. After some calculus, for an exponential function with normalized amplitude we obtain:

$$T_2^* = -\frac{\sum_{n=0}^{N-1} t_n}{\sum_{n=0}^{N-1} \ln f_n}, \qquad (2)$$

where $f_n=|a_n|$ is the absolute amplitude value of the nth extreme point. Note that for a normalized exponential decay function, T_2^* is the unique needed parameter.

In order to perform the matching comparison, we redefine the parameters of eqn. (1):

$$\begin{aligned} M_a &= \sum_{n=1}^{N} \frac{f_n}{N} \\ D_a &= \sum_{n=1}^{N} \frac{|f_n - M_a|}{N}. \end{aligned} \qquad (3)$$

These last expressions are more convenient for the calculus since we are processing the positive envelope of the signal. The measured time intervals between extreme points of the signals are regular (see Fig. 1), particularly when the envelope is close to an exponential decay. Because of this fact, the time parameters D_t and M_t defined in eqns. (1) fail in providing an adequate discrimination between different signals. For this reason we discard these parameters in our algorithm. Then we focus the matching comparison through the amplitude parameters of eqns. (3). After some math, the values of M_a and D_a corresponding to an exponential decay are:

$$\begin{aligned} M_a^\infty &= \frac{T_2^*}{T}\left(1 - e^{-T/T_2^*}\right) \\ D_a^\infty &= 2\frac{T_2^*}{T}\left[1 - M_a^\infty\left(1 - \ln M_a^\infty\right)\right], \end{aligned} \qquad (4)$$

for a large enough number of extreme points N, where T is the total measuring time. Like in the standard SSC method, we calculate the error between the values M_a and D_a corresponding to the acquired signal, and the values M_a^∞ and D_a^∞ associated to the target exponential decay. In these last expressions, T_2^* is obtained from eqn. (2). The matching errors can thus be obtained from:

$$\begin{aligned} d_{Ma} &= \frac{|M_a - M_a^\infty|}{M_a^\infty} \\ d_{Da} &= \frac{|D_a - D_a^\infty|}{D_a^\infty}. \end{aligned} \qquad (5)$$

The main difference between the standard SSC method and the version here proposed relays in the fact that the former uses a table of parameters calculated from known signals, and the latter uses theoretical parameters obtained for the best fitting of known functions to the measured signals. Therefore, while the standard method uses static SSC parameters, our method use dynamic SSC parameters. For a higher quality of the characterization, we are including a new parameter d_m that measures the amplitude mean deviation error of the envelope respect the exponential decay target:

$$d_m = \frac{1}{N}\sum_{n=0}^{N-1}\left|f_n - e^{-t_n/T_2^*}\right|.$$

Finally, the discrimination function will be written in terms of T_2^*, d_{Ma}, d_{Da} and d_m. It is worth to note that the exponential and logarithm functions appearing in the previous equations can be obtained from tables with pre-calculated values. Therefore, the time spent in the calculus does not affect the speed of the algorithm in embedded systems.

IV. DISCRIMINATION FUNCTION

The discrimination function represents the last instance that will finally reflect the quality of the magnetic field homogeneity. Its choice is relevant since it will define the sensibility of the discrimination process. In this case, three different functions where considered. A first test was done with the function:

$$f_d = -\frac{T_2^*}{T}\log\left(d_{Ma} d_{Da} d_m\right).$$

This discrimination function is proportional to T and in inverse to the errors d_{Ma}, d_{Da} and d_m. These last are smaller when the FID envelope approximates to an exponential. As the error parameters are affected by the log function, they may take very small values without giving values of f_d too big. A limitation of this function is that not all the errors have the same weight, as suggested from the expression. In the practice, it was found that d_m is much better correlated to the exponential character of the FID. For example, we have found that d_{Ma}, and d_{Da} may decrease their values when the signal deviates from an exponential decay. In addition, all error parameters must be positive to have the discrimination function defined. On these grounds we look therefore to a second option:

$$f_d = T_2^* \log\left(\frac{p_{Ma}}{1+d_{Ma}} + \frac{p_{Da}}{1+d_{Da}} + \frac{p_m}{1+d_m} + 1\right),$$

where the p_j are the weithing factors. The included “plus one” term ensures that f_d remains finite independently of the values that the errors may take. This last expression allows to adjust the relative contribution of the different errors, but not contribution of T_2^* in an independent way (since it appears as a common factor for all the terms). Then we define:

$$f_d = T_2^* + \frac{p_{Ma}}{1+d_{Ma}} + \frac{p_{Da}}{1+d_{Da}} + \frac{p_m}{1+d_m} \tag{6}$$

This last discrimination function proved to be the best for the shimming purposes as explained before.

V. PRACTICAL IMPLEMENTATION AND HARDWARE

The homogenization procedure consists in the finding of the optimal set of currents that drives the shim coils to the maximum homogeneity condition. Considering all possible configurations (here, a configuration refers to a given set of currents) is an inefficient procedure since the configuration space may be extremely large (for instance, 256^4 possible configurations in our case). An alternative procedure consists in a step-by-step iteration where the current of each coil is successively optimized. The successive approximation procedure can be summarized in the following steps:

- Scan the current at each coil at time in order to rank their influence on the magnetic field homogeneity. During the current scan at one coil, the current of the rest of the coils is set to zero.
- Assign a step-size for the current scan. The step size is larger for less-relevant coils.
- Start the scanning process in the first coil of the ranking (higher effect on the homogeneity for a same current variation) with the assigned step-size. Once the largest f_d is found, reduce the step-size and repeat scan in a region around the optimal value. The process may be repeated until the desired convergence. Then switch to the next coil in the ranking and repeat process (while keeping the current fixed in the previous).
- After completing the scanning process in all the coils, the obtained FID should correspond to the optimized shimming condition.

Several details were skipped for the sake of simplicity. However, the essential procedure was based on these grounds.

A four-channel system was developed to test the concept. A processor unit reads the FID signal with a 10 bits analog to digital converter (ADC) each time a synchronism pulse indicates. The synchronism pulse is obtained from the NMR instrument used to generate the FID (and whose magnetic field homogeneity is being adjusted). All the process is monitored by a program in a command module running on a personal computer (PC) communicated with the controller by a serial connection. The same program also serves to pass orders and configuration parameters to the shimming algorithm. Fig. 2 shows a simplified block diagram of the complete system.

The control tasks are carried out by a dedicated data acquisition processing board based on a dspic30f3013 Microchip digital signal controller (DSC). Analog signals arrive to the DSC A/D converters through an instrumentation amplifier which has configurable gain, offset and a band-pass filter for input signal conditioning. Once the controller shim algorithm has converged, optimal currents are driven from a power supply that communicates with the controller using a RS323 serial connection.

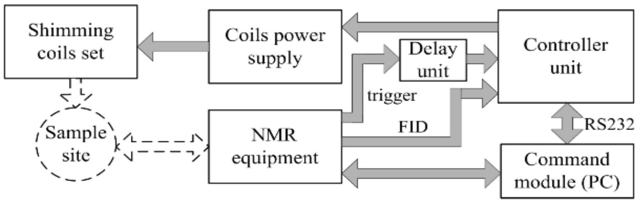

Figure 2. Simplified block diagram of the system involved in the automatic shimming process.

The command module consists in PC running application software which allows the user to configure and monitor the whole shimming process. It allows the configuration of the three weighting parameters of f_d (p_j), the algorithm trigger level, the tolerance for the error parameters, a simple moving average filter (MAF) length applied to the feedback FID signal, and all other configurable parameters of the process.

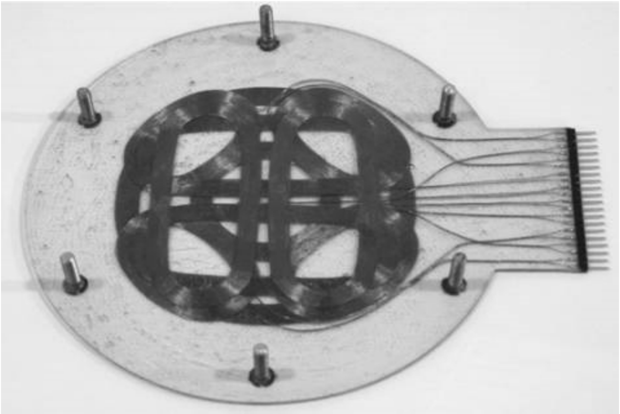

Figure 3. Shim coils.

Pairs of anti-Helmholtz coils were used to test the system. Optimized coils may be calculated for each application. However, details of the coil calculations are outside the scope of the present work. Anti-Helmholtz configuration coils are often used as shim coils. Shim coils generate magnetic field gradients, which depending on its geometry, will produce a specific type of gradient. Variation of the external magnetic fields may exist in a variety of functional forms like linear, parabolic or other. Therefore, a variety of coils of different geometry has to be conveniently implemented in order to contribute to each type of functional form. The design was performed to adapt the coils to the dimensions of our resistive magnet which posses a circular pole face with a diameter of 10 cm and a gap of 2.5 cm. Each coil was built with 20 turns of copper wire with a diameter of 0.25 mm. Ten pairs of coils were arranged and stuck together using polyester resin in a kind of disc as shown in Fig. 3. The total thickness of the disc is 2.5 mm. The six screws sown in the figure are used to fix the disc to the polar face of the magnet. The photograph shows one of the set of ten shim coils which is attached to one of the magnets pole face. A similar mirror set of coils was built, which is attached to the opposite pole face of the magnet.

VI. PERFORMANCE TEST

Since the digital control module has only four channels, we selected from the ten coil pairs those that are more influent on the magnetic field homogeneity. Even though our shim coil set was sufficiently favorable for the purpose of this work, a more precisely design of the coils can be performed.

The test here reported was performed using the discrimination function defined in eqn. (6). Relevant configurable parameters are:

- Step-size for coil ranking: 50
- Step-size for shimming process: 16
- Total samples: 60
- d_{Ma} tolerance: 0.20
- d_{Da} tolerance: 0.30
- d_m tolerance: 0.15
- p_{Ma} and p_{Da}: 0.1
- p_m: 1
- Sample frequency: 122.880Hz

The change in the FID signal after executing the automatic shimming process can be observed in Fig. 4. The result reflects a clear improve of the magnetic field homogeneity.

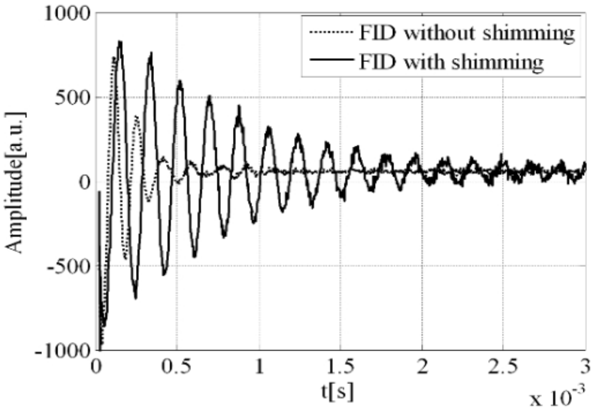

Figure 4. FID signals before and after the automatic shimming process.

Relevant parameters have changed after the shimming process as reported in table I. At first sight, from Fig. 4 we see that the FID after shimming has doubled the time decay, while the T_2^* parameter remains nearly the same for both signals. This is a consequence from the fact that the FID before shimming still oscillates at times larger than 2s, corresponding to a non-exponential decay of the envelope. However, as can be seen in the table, the error parameters decreases after shimming, indicating that the shimmed signal envelope is closer to an exponential decay.

TABLE I: SSC parameters before and after the shimming process.

Parameter	Initial value	Final Value
d_{Ma}	0.69	0.031
d_{Da}	0.5	0.032
d_m	0.2	0.07
T_2^*	0.127	0.120
f_d	0.87	1.01

VII. CONCLUDING REMARKS

The example developed in this paper shows that the SSC method can be successfully adapted for the control of a process based on the statistical characterization of a feedback signal. A modified version of the method based on the definition of dynamical statistical parameters was here introduced.

The noticeable improvement in the FID signal (Fig. 4) corresponds to a successful compensation of the magnetic field homogeneity. For a given set of shim coils, the quality of the shimming depends on the choice of the statistical parameters and discrimination function. In the present example, the final performance can still be much improved through the addition of more channels/coils and/or by refining the coil design in order to optimize their shape according to the main geometry imposed by the main magnetic field to be shimmed.

The method is fast, allowing a convergence in a few scans. Even when the total time will increase with the addition of new channels, still has the advantage of its intrinsic simplicity over other established methods.

The methodology can be extended to other iterative control applications based on digital process of a feedback signal.

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Héctor H. Segnorile received the Engineering degree in Electronics Engineering from Universidad Tecnologica Nacional - Facultad Regional Cordoba, Cordoba, Argentina, in 2006, the degree and the PhD in Physics from Universidad Nacional de Córdoba (UNC), Cordoba, Argentina, in 2003 and 2009, respectively. He has been working for the Argentina's CONICET as a researcher since 2012 in Instituto de Fisica Enrique Gaviola - UNC. His current research interest is the theoretical and experimental study of decoherence in open quantum systems, using Nuclear Magnetic Resonance techniques.

Guillermo Omar Forte was born in Marcos Juárez, Argentina, in 1976. He received the Engineering degree in Electronic Engineering in 2002 and the Master´s degree in Automatic Control in 2008, both from Universidad Tecnológica Nacional (UTN), Córdoba, Argentina. He is currently a PhD student in Engineering in Univ. Nac. Córdoba. He is Professor of Artificial Intelligence at UTN since 2006. His current research interest includes magnetic fields control for FFC-NMR applications.

German David Farrher received the M. Sc. in physics in 2001 from Universidad Nacional de Córdoba (UNC), Córdoba, Argentina, and the PhD. degree in Physics from Universität Ulm, (Germany). He has been working for the Argentina's CONICET as a researcher since 2007. He is Professor at UNC since 2007. His current research interest includes NMR imaging experiments and magnetic fields control for FFC-NMR applications.

Esteban Anoardo received the PhD. degree in physics from Universidad Nacional de Córdoba (UNC-Argentina) in 1990. He holds a Professor position at FaMAF - UNC where he leads the LaRTE lab. He was an Alexander von Humboldt Fellow at Sektion Kernresonanzspektroskopie, Universität Ulm (Gemany) and R&D Coordinator at Stelar srl in Italy. His research interests include a mix of NMR hardware and its applications in selected topics. He is fellow of CONICET at the Enrique Gaviola Physics Institute (IFEG) and Coordinator of the Physics Section at FaMAF. He also serves on the Director Board of the technology incubator of Famaf (IEBTF).