Data Transfer and Processing in MR Tomography using Digital Signal Processor

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Abstract: - The application of a DSP96002 digital signal processor in measuring and transferring data, setting the pre-emphasis constants, and communicating with the MR tomograph is described in the paper. The application of the digital signal processor represents a modern approach to real-time processing of MR signals. The objective is to obtain distance communication with the tomograph via the Internet.

Key-Words: - Digital signal processor, MR tomograph, fast imaging methods, pre-emphasis filter, gradient controller

1 Introduction

Nuclear magnetic resonance experiments require three mutually orthogonal gradients of magnetic field, $G_z = \delta B_z/\delta_z$, $G_y = \delta B_z/\delta_y$, $G_x = \delta B_z/\delta_x$, which either encode spatial information in tomograph image or they eliminate undesirable effects in one- or two-dimensional spectra [1]. Fast switching of magnetic field gradients is here a major problem, in particular when using fast imaging methods in which very short gradient impulses (< 5 ms) are used, and in localized spectroscopy where spectra are detected from regions that are precisely defined by gradients. In the vicinity of gradient coils, fast changes of the field induce eddy currents in conducting materials which are responsible for the time delay of the change in magnetic field and extend inordinately the time the gradient field takes to settle at the inhomogeneity level of the basic magnetic field of spectrometer (the usual time to obtain steady-state field is > 2 s). Magnetic field therefore changes during the detection of the signal measured, and its spatial distribution also changes. In MR tomography the action of eddy currents is responsible for the geometrical distortion of the image being detected (it is detected from a very inaccurately defined layer) while in spectroscopy (both multi-dimensional and localized) it leads to the appearance of undesirable interference signals in the spectra.

Today it is required that any gradient with an amplitude of more than 100 m/Tm should drop, in less than100μs, to the inhomogeneity level of the basic field, which in tomography is 3.9 μT/m, in NMR microscopy 15 μT/m, and in spectrometry 2.3 μT/m [2].

One of the methods for eliminating the effect of eddy currents is pre-emphasis compensation [1], [3], [4]. This involves exceeding the current impulse flowing through the gradient coil in a precisely defined multiexponential way, namely such that the gradient magnetic field will drop to zero in less than 100 μs. The exact parameters of pre-emphasis compensation can be established by analysing the measured time course of the decay of gradient magnetic field in the working space [3], [5]. The measuring accuracy must be very high (> 0.1%).

2 Pre-emphasis Filtering

Fig. 1 shows the block diagram of pre-emphasis digital filters and their connection to the model of tomograph magnet [5]. The $P_\alpha(z)$ blocks are referred to as *direct* *filters,* the $P_{\alpha 0}$(z) blocks as *cross filters*. The H_x(z) blocks represent gradient coil transfers while the H_{x0}(z) blocks are cross transfers between individual coils.

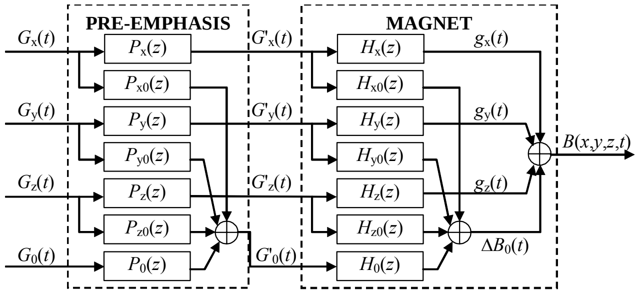

Fig. 1 *System of pre-emphasis digital filters and its connection to tomograph magnet.*

The term 'ideal state' will be used to refer to a state when pre-emphasis filters have such parameters that the waveforms of gradient components of magnetic field correspond to their excitation ($g_{x,y,z} = G_{x,y,z}$) and, at the same time, there are no undesirable changes in the basic field ($\Delta B_0 = 0$). Under this condition it is possible to determine the transfer characteristic of direct and cross pre-emphasis filters in the form:

$$P_\alpha = \frac{1}{H_\alpha} = \frac{1}{\sum_{k=1}^{N} A_k \frac{1-D_k}{z-D_k}} = K \cdot \frac{(z-D_1)\ldots(z-D_N)}{(z-Z_1)\ldots(z-Z_{N-1})}, \tag{1}$$

$$P_{\alpha 0} = K \cdot (z-1)\frac{(z-z_1)(z-z_2)\ldots(z-z_{N+N'+N''-1})}{(z-p_1)(z-p_2)\ldots(z-p_{N+N'+N''-2})}. \tag{2}$$

where K is the filter gain, which depends on the values of all constants A_k and D_k, and α represents the coordinates x, y or z. It is obvious that the zeros of pre-emphasis filter P_α are identical with the poles D_k of the corresponding direct magnet transfer H_α, and vice versa. If we assume that the magnet transfer function is stable, then for the coefficients D_k it holds $0 \le D_k < 1$ (i.e. $T_k \ge 0$).

The pre-emphasis filter coefficients can be established by measuring the response to the unit step of gradient G_α and the induction of magnetic field B, with the other two gradients being zero. On this assumption and in keeping with Fig. 1 it holds

$$B = \alpha G_\alpha P_\alpha H_\alpha + G_\alpha\left(P_\alpha H_{\alpha 0} + P_{\alpha 0} H_0\right), \tag{3}$$

$$\alpha G_\alpha = \alpha G_\alpha P_{\alpha i} H_\alpha + G_\alpha\left(P_{\alpha i} H_{\alpha 0} + P_{\alpha 0 i} H_0\right). \tag{4}$$

By measuring [6] in two mutually opposite thin sections with coordinates α and $-\alpha$ we obtain the following system of equations

$$\begin{aligned}
B(\alpha) &= \alpha G_\alpha P_\alpha H_\alpha + G_\alpha\left(P_\alpha H_{\alpha 0} + P_{\alpha 0} H_0\right)\\
B(-\alpha) &= -\alpha G_\alpha P_\alpha H_\alpha + G_\alpha\left(P_\alpha H_{\alpha 0} + P_{\alpha 0} H_0\right)\\
\alpha G_\alpha &= \alpha G_\alpha P_{\alpha i} H_\alpha + G_\alpha\left(P_{\alpha i} H_{\alpha 0} + P_{\alpha 0 i} H_0\right)\\
-\alpha G_\alpha &= -\alpha G_\alpha P_{\alpha i} H_\alpha + G_\alpha\left(P_{\alpha i} H_{\alpha 0} + P_{\alpha 0 i} H_0\right)
\end{aligned} \tag{5}$$

Their solution yields relations for the transfers of pre-emphasis filters $P_{\alpha i}$ and $P_{\alpha 0 i}$ in the form

$$P_{\alpha 0 i} = \frac{1}{H}\left[\frac{P_{\alpha i}}{P_\alpha}\left(H\,P_{\alpha 0} + \frac{B(\alpha) - B(-\alpha)}{2\alpha H_0}\right)\right] \tag{6}$$

$$\frac{H - G_\alpha}{P_{\alpha i}} = H - \frac{B(\alpha) - B(-\alpha)}{2\alpha P_\alpha} \tag{7}$$

where H is the image of unit step.

These transfers can be approximated by multiexponential functions and then constants of pre-emphasis filters A_{ki} and D_{ki} of direct and cross transfers can be determined.

3 Application of Digital Signal Processor

Prior to determining the pre-emphasis constants it is necessary to measure precisely the time course of gradient magnetic field after the termination of gradient pulse. A new gradient system has been proposed and designed, which solves the complex of the measurement of pre-emphasis constants, their transfer and processing. At the same time it serves to set the basic magnetic field homogeneity, using the matrix shims feeding device, and to perform tomograph measurements. This system is based on the Motorola DSP96002 digital signal processor. This digital signal processor has the dual Harvard architecture with a bus width of 32 bits and operates with floating-point arithmetic. Its parallel operation and high computation power meets the demands of the given application. At the beginning of the NMR experiment the data and the program are transferred via communication channels. After the start, the digital signal processor waits for the arrival of control impulse from the pulse generator and then performs for the required gradient amplitude in real time the pre-emphasis compensation, successively for all the channels whose parameters are saved in its memory. Via 16-bit D/A converters and gradient power amplifiers the output signals excite current impulses into gradient coils. The sampling of gradients has a repetition frequency of 25 kHz. For the sake of precise measurement of pre-emphasis constants the gradient system has been complemented with a fast 12-bit A/D converter (200 kHz). The block diagram of the whole gradient tomograph system can be seen in Fig. 2.

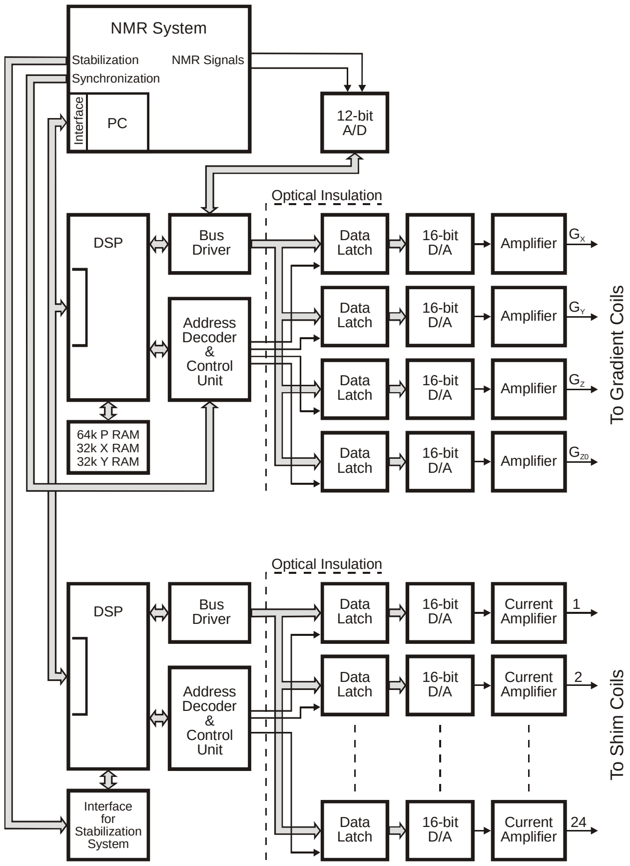

Fig. 2 *Block diagram of gradient system with digital signal processor*

The high computation power of the digital signal processor has enabled setting the required magnitudes of the gradients, their timing and the calculation of pre-emphasis filtering in four channels in a minimum time of 35 µs so that time intervals can be set with this step. Even shorter times have been achieved since the shortest currently used lengths of gradient impulses range from 0.5 ms to 1ms. For the application of conventional MR imaging techniques (Spin-echo or Gradient-echo) this step length is sufficient. When the MR tomograph is turned on, the initialization of MR system takes place. Data blocks are transferred from the host computer into all autonomous systems in order to initialize the MR system. For the gradient system, a program of 25 Kbyte in size is transferred, the gradients are reset, and the correction currents for homogenizing the basic magnetic field are set. The time if initializing the MR system is not important. In the measuring mode the measurement parameters and values of constants are transferred into all autonomous systems after the start of experiment. For the gradient system, a data block of 32 Kbyte is transferred in 51 ms. For MR experiments this time is critical because it slows down the start of a new experiment with altered parameters. In the techniques of measuring the relaxation times of the sample being measured and MR images weighted by the flow rates of the sample being measured or by the relaxation properties of cores the time of starting the new experiment is critical. It should be less than a few hundreds of ms. that provides for meeting the time limit of data transfer.

The gradient system should be set and started in less than 75 ms. For this purpose it will be necessary to design a new fast communication channel.

4 New Communication Interface for DSP96002

For the purposes of NMR tomography and measuring the gradient field decays a new type of communication between the host computer of the PC AT type and several remote independent Motorola DSP96002 digital signal processors was solved [8], [9], [10]. The aim was to replace the initial Motorola solution of the development system, i.e. PC interface board - Command converter with DSP56001 digital signal processor - target application with DSP96002, by a simpler solution where there is no need to assign always one Command converter to each application with a DSP96002, and to prepare short service routines in order to avoid using the large development environment in mere data transfer. This resulted in not only simplifying the whole instrument but also reducing the cost.

In the new device the option of connecting several applications with DSP96002 to one interface board remains preserved. From the circuit point of view the board comprises these parts: serial-parallel shift register, time base, control unit, signal output drivers `DSI`-(`OS0`), `DSCK`-(`OS1`), `DR` and `RESET`, signal input circuits `DSO`, (`DSI`)-`OS0`, (`DSCK`)-`OS1`, and delay unit.

The 16-bit parallel-to-serial shift register converts 8-bit commands or 32-bit data to serial form. Via an output three-state driver with addressing, this information is applied to the `DSI-OS0` input of the processor. Via the input multiplexer the data are conveyed from the `DSO` output of the processor to the 16-bit serial-to-parallel shift register, which converts 32-bit data to the parallel form.

The time base, controlled by a crystal oscillator, is the signal source for synchronous serial transfer. It generates groups of eight or sixteen pulses, depending on whether the transfer of a command or data is concerned. These pulses are applied to the two shift registers and, via the output three-state driver with addressing, to the `DSCK-OS1` input of the processor.

The DEBUG-REQUEST signal is program-generated and applied, via the output driver with addressing, to the DR input of the processor. The RESET signal is also program-generated and conveyed, via the input driver, to the RESET input of the processor. The control unit decodes the addresses and the other ISA bus signals, and controls the activity of the other circuits on the board. The delay unit is formed by a chain of gates, which delay the clock signal designed for the serial-parallel register by the same time (several tens of ms) as the signal delay during the passage through cable to the digital signal processor and back.

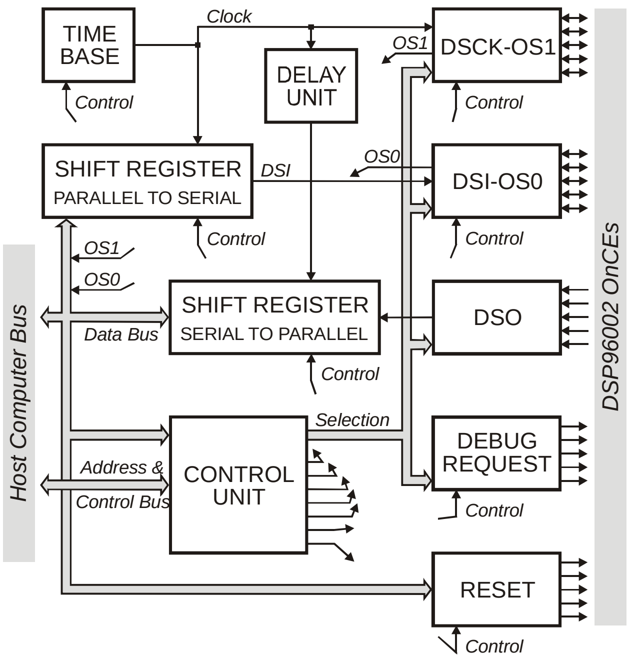

Fig. 3 *Block diagram of communication interface.*

Three mutually independent programs have been created that can be started from the files – dspread, dspwrite and dspreset. The dspread program reads the X:, Y: or P: memory segments depending on the parameters set in the instruction, and saves the read data in the *.lod text file, which is compatible with Motorola programs and supplied with the development system. The parameters set in the instruction are these: file name, port number, type of memory (X:, Y:, P:), initial address, and number of 32-bit words. The dspwrite program saves the content of the *.lod text file in the DSP96002 program memory. Depending on the parameter in the instruction the program can start running from the initial address given in the *.lod file. The parameters set in the instruction are these: file name, port number and possibly start. The dspreset program performs the initial setting (RESET) of connected DSP96002 digital signal processors according to the parameter on the command line. It is designed for simultaneous starting of two or more digital signal processors in cases when successive starting via the dspwrite file is not satisfactory.

Communication via the debug port of the DSP96002 digital signal processor is sufficiently fast (the clock rate can be set in the range form 0.5MHz to 8MHz along the length of the serial line) and is satisfactory in most applications. The solution described above makes the deployment of DSP96002 cheaper in cases when its communication with a master computer of the type of PC AT is necessary, and it facilitates data transfer in that it is not necessary to use the development environment with every transfer.

5 Conclusion

A simpler gradient controller and a matrix shims feeding device have been developed that ensure the high performance required for modern pulsed gradient MR experiments. Using a DSP96002 digital signal processor, pre-emphasis filtering is performed in four channels in 34 μs/sample, with the gradient magnetic field falling to the level of basic field homogeneity in 0.5 ms. The new Internet communication between the DSP and the control computer with a clock rate of 8 MHz is no limiting factor in measuring the MR of tomograph images.

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Acknowledgement

The paper was prepared within the framework of N°IAA2065201 *project of the Grant Agency of the Academy of Sciences of the Czech Republic and with the support of the research plan* CEZ: J22/98:262200011.