Two Approaches to Measurement of the Signal Frequency in NMR Based Magnetic Field Stabiliser

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Abstract: *The phenomenon of nuclear magnetic resonance (NMR) in a water sample was used for magnetic field stabilisation. Signal processing from the NMR probe is performed in digital way to prevent drifts and distortions in circuits for analogue signals processing. The signal is analysed with FFT and the frequency deviation to the desired frequency of the highest peak is taken as a ground for the control. Basing on a theoretical analysis the circuit diagram has been selected and the first sample of the stabiliser with digital signal processing has been constructed. Such type of stabiliser can be used for magnetic field stability of NMR scanners with permanent or resistive magnets increasing.*

1. Introduction

The magnetic field stability in NMR scanners with resistive magnets is not too high. It must be increased with a suitable stabiliser for quality data measurement. NMR based magnetic field stabiliser was described in [1]. Free induction decay (FID) signal from its NMR probe was processed by analogue circuitry and used for basic magnet current regulation. Nevertheless working points of analogue circuits are sensitive to many factors eg temperature, supply voltage stability and so forth. That's why the stabiliser was updated with an adaptive unit for drifts of analogue signals compensation [2,3]. Even so the linear work span of the circuitry was not very high. Another way of signal processing is its digitisation and computing. The frequency of the strongest signal in the spectre is revealed by the discrete Fourier transform [4,5,6] and basing on its frequency deviation to the required for the desired value of the magnetic field the regulation signal is calculated for the current supplying a resistive magnet. The purpose of this paper is a theoretical analysis of processing requirements determining the ultimate circuit diagram of the stabiliser. The theory was verified on the first sample of the NMR stabiliser with digital signal processing.

2. Theoretical Analysis and Design

FID signal from a water sample of the stabiliser probe can be with a simplification described by the formula

$$s(t) = (U_o e^{\mathrm{j}(\omega_o t+\varphi_o)} + \sum_{i=1}^{n} U_i e^{\mathrm{j}(\omega_i t+\varphi_i)}) e^{-\frac{t}{T_2^*}},$$

where T_2^* is the weighed transversal relaxation time, *t* is the time. The term in front of the sum is the strongest part of the signal corresponding to the basic magnetic field strength. The terms in the sum are contributions of the basic magnetic field inhomogeneities within the sample volume. The inhomogeneities contribution should be much smaller than that represented by the first term. The angular frequency ω_o is determined as $\omega_o = \gamma B_o$, where γ is the gyromagnetic ratio and B_o is the magnetic field strength (similarly for the terms behind the sum). The signal from the probe is sampled equidistantly with the sampling interval *T*. The *i-th* time domain sample of the signal *s(t)* can be written as $s_i = s(iT)$, where *i= 0,1,2...N-1*. The transformation of the sampled *s(t)* signal into the frequency domain yields the *k-th* frequency sample

$$S_k = \sum_{i=0}^{N-1} s_i e^{-\mathrm{j}ik\frac{2\pi}{N}}, \; k=0,1,2...N-1.$$

The angular frequency of the *k-th* frequency sample is

$$\omega_k = \frac{k\,2\pi}{NT}.$$

It means the output signal frequency varies with the step

$$\Delta\omega = \frac{2\pi}{NT}.$$

Consider sampling and converting a signal with the angular frequency ω_{real}. The sampling interval T_{real} is derived from a clock frequency and is really trimmed to that value. Nevertheless in the calculation of the FFT the sampling interval $T_{\sup}$ is supposed (eg according to the manufacturer's data). After the transformation the signal corresponds to the $k_{real} - th$ frequency sample where

$$k_{real} \cong \frac{\omega_{real} N T_{real}}{2\pi}.$$

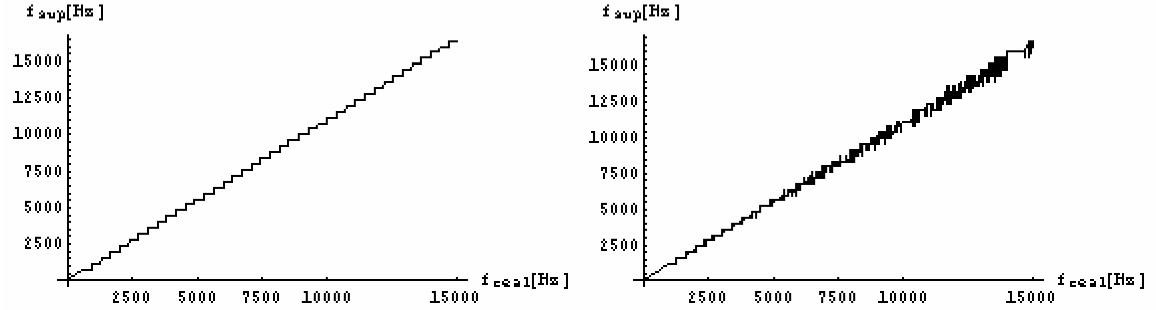
The value is only approximate because of discontinuity of the discrete Fourier transform. It must be rounded to the closest integer. The rounding can cause a maximal error of ± 0.5. Nevertheless the sampling interval T_{real} is also determined with a finite accuracy in technical practice (eg temperature drifts). Number of the frequency sample corresponding to the signal frequency is then

$$k_{real} = \frac{\omega_{real} N T_{real}}{2\pi} \pm \left(\frac{\omega_{real} N}{2\pi} \Delta T_{real} + 0.5\right).$$

Subsequently the angular frequency $\omega_{\sup}$ resp. $f_{\sup}$ of the signal as a result of computer processing (Fig. 1.) is calculated as follows:

$$\omega_{\sup} = \omega_{real} \frac{T_{real}}{T_{\sup}} \pm \left(\frac{\omega_{real}}{T_{\sup}} \Delta T_{real} + \frac{\pi}{N T_{\sup}}\right).$$

Increasing the frequency of the signal the error increases as well. Besides, the calculated frequency of the signal $\omega_{\sup}$ differs from that actual ω_{real} due to inaccurate trimming of the clock generator. Nevertheless the difference can be removed by recalculation of the $\omega_{\sup}$ value after calibration of the circuits with a signal with sufficiently high frequency accuracy and stability. The suitable conception of circuitry can minimise the frequency tolerance due to ΔT_{real} and a sufficiently fine sampling can suppress the influence of the rounding.



a) b)

Fig.1. The calculated frequency versus the signal frequency: a) $T_{\sup} = 10^{-5}$, $T_{real} = 1.1 \times 10^{-5}$, $N = 250$, $\Delta T_{real} = 0$; b) the same but T_{real} changes randomly by max. $\pm \Delta T_{real} = 5 \times 10^{-7}$. Of course ΔT_{real} does not vary from sample to sample in practice.

Fig. 2. offers the first possible circuit diagram. The amplified FID signal from the NMR probe is detected in the quadrature detector QD. The detector transforms the frequency ω_o into zero value (if

the desired magnetic field strength is available) with help of an oscillator OSC, the detected signal has its real and imaginary parts. The both parts of the signal are sampled, converted into digital form and the discrete Fourier transform is performed (FFT). Subsequently the frequency of the strongest spectre component ω_o is revealed. Its deviation from the frequency corresponding to the desired magnetic field strength determines the parameters of the regulation signal (REG). Thanks to zero-close value of the frequency of the detected signal, the errors of frequency calculation by the discrete Fourier transform can be very efficiently suppressed. On the other hand the zero-close frequency of the signal requires its both parts the real and the imaginary to determine whether the frequency deviation corresponds to a positive or a negative deviation of the magnetic field. To simplify the circuits of detector, another version of the circuitry was also considered (Fig. 3.).

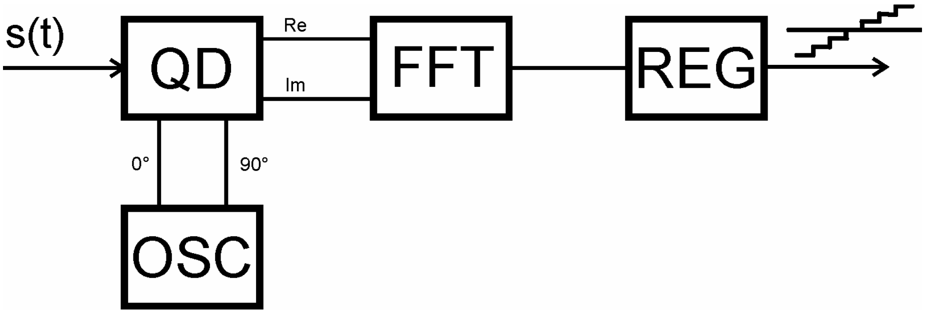


Fig. 2. Digital signal processing with quadrature detector

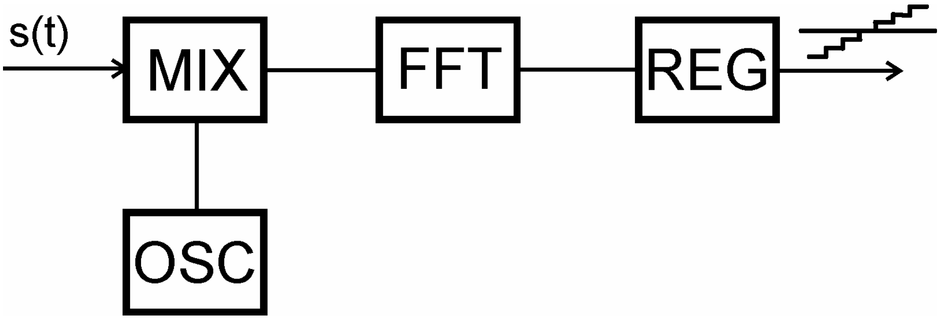


Fig. 3. Digital signal processing with mixer

The quadrature detector is replaced with the mixer MIX converting the ω_o frequency into a non-zero value. The mixer circuitry is much simpler than the quadrature detector circuitry and also program for the discrete Fourier transform is simpler because the input signal has only the real part. The circuitry is simpler in the second case nevertheless the demands on sampling and A/D conversion of the signal are higher for higher value of ω_o frequency.

3. Results and Discussion

The second block diagram (Fig. 3.) has been selected for the realisation but the ω_o frequency is converted to only 1 kHz. Analogue circuitry of the realised stabiliser sample has been acquired converting circuitry of an unused home made emitter/receiver unit. The construction is cheap and easy-to-make. After the sampling and the A/D conversion of the FID signal from the excited water sample by a PC based I/O module the discrete Fourier transform has been performed in the PC and the frequency deviation is calculated. Subsequently a signal appeares at the output of the I/O module available for the basic magnet's current regulation. The basic magnetic field of an NMR scanner should not vary from its nominal value by more than 1 ppm for good quality of scanned images ensuring. The stabilisation is performed in breaks between two (or more) neighbouring scans and the output regulation signal lasts until the next stabilisation. The desired magnetic field can be achieved in several gross and fine steps.

The control program for the stabiliser has to calculate the frequency corresponding to the maximum of the $\{|S_o|,|S_1|,\ldots|S_k|,\ldots|S_{N-1}|\}$ sequence. Based on the calculated frequency and the desired frequency the frequency deviation is calculated and the output signal for magnet supplying regulation is generated.

The stabiliser was used in connection with a whole-body home made NMR imager 0.1 Tesla. An auxiliary program has been written calculating the discrete Fourier transform of a harmonic finally lasting signal simulating situation in the stabiliser. The information depicted in Fig. 1. has also been calculated with the program.

In practical application the magnetic field of the scanner with the stabiliser was varying closely to the desired value during the measurement. The deviation has not exceeded 5 ppm (peak-to-peak) in our experiments (the frequency step corresponding to approx. 1 ppm) within several minutes. Nevertheless such altering magnetic field during a measurement can influence the resulting data quality. Suppressing the magnetic field changes and qualitative analysis of the additive noise and its influence on measured data quality are tasks for the future. The analysis should reveal qualities of the created noise and indicate ways of suppressing its influence.

4. Conclusion

The experiments with static magnetic field stabilisation based on digital signal processing from the NMR phenomenon in water sample have confirmed the previous considerations. The stability and accuracy of the stabilisation have been increased significantly and complexity of the used circuitry has been reduced. Magnetic field stabilisation in this manner is energy saving because the magnet is prepared for its work in a short time. Results of the experiments can be used for other versions of the stabiliser design.

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