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TUTORIAL 4681

Introduction to Magnetic Resonance Imaging (MRI)

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Abstract: This tutorial explains how magnetic resonance imaging (MRI) systems use the reaction of hydrogen atoms moving in a magnetic field to yield a detailed medical image. The types of magnetic fields typically used are described. The note explains why today's higher resolution MRI systems rely on super-conducting magnets. The note also discusses the formation of 3-D images by proper alignment of gradient coils and their interaction with RF signaling. A functional block diagram of a typical MRI system is presented.

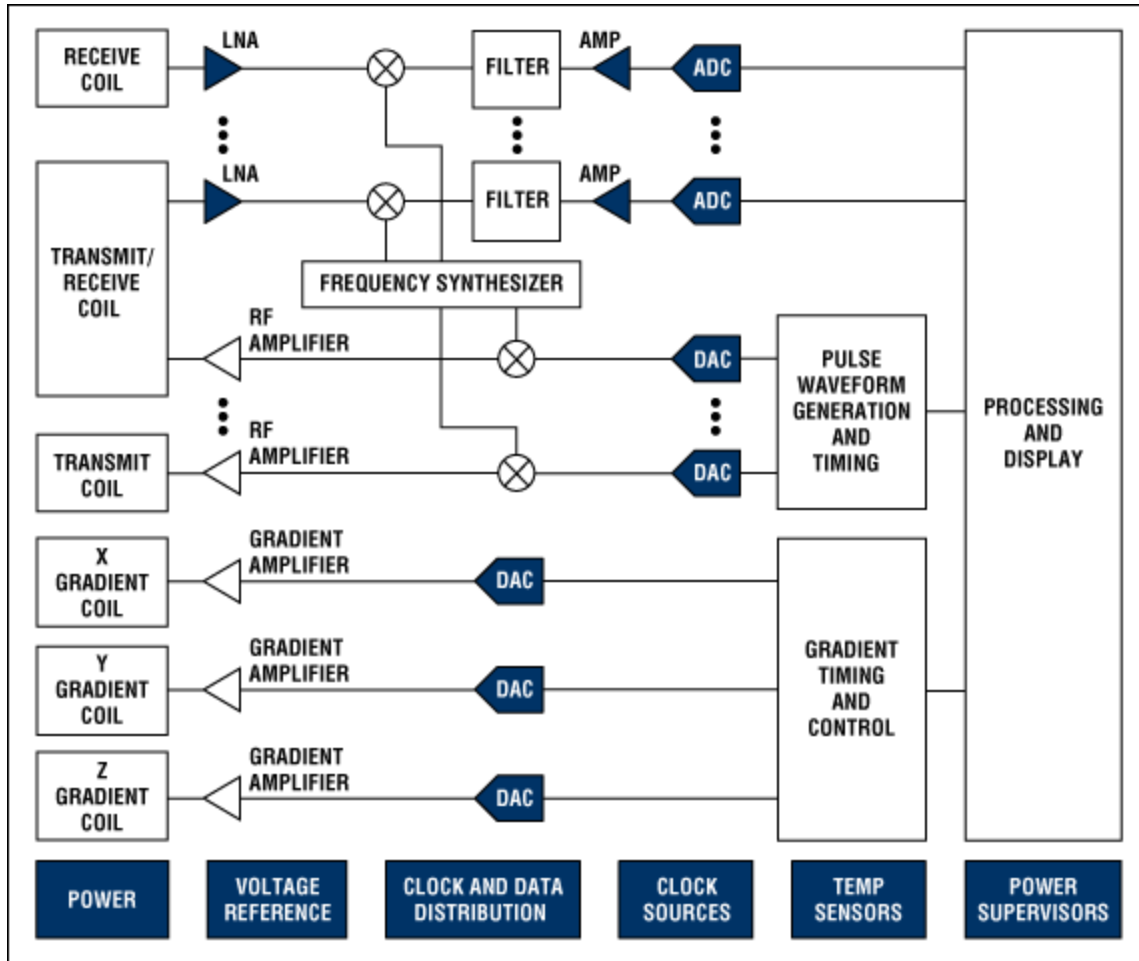
Overview

Magnetic resonance imaging (MRI) systems provide highly detailed images of tissue in the body. The systems detect and process the signals generated when hydrogen atoms, which are abundant in tissue, are placed in a strong magnetic field and excited by a resonant magnetic excitation pulse.

Hydrogen atoms have an inherent magnetic moment as a result of their nuclear spin. When placed in a strong magnetic field, the magnetic moments of these hydrogen nuclei tend to align. Simplistically, one can think of the hydrogen nuclei in a static magnetic field as a string under tension. The nuclei have a resonant or "Larmor" frequency determined by their localized magnetic field strength, just as a string has a resonant frequency determined by the tension on it. For hydrogen nuclei in a typical 1.5T MRI field, the resonant frequency is approximately 64MHz.



Proper stimulation by a resonant magnetic or RF field at the resonant frequency of the hydrogen nuclei can force the magnetic moments of the nuclei to partially, or completely, tip into a plane perpendicular to the applied field. When the applied RF-excitation field is removed, the magnetic moments of the nuclei precess in the static field as they realign. This realignment generates an RF signal at a resonant frequency determined by the magnitude of the applied field. This signal is detected by the MRI imaging system and used to generate an image.



Block diagram of an MRI imaging system. For a list of Maxim's recommended MRI solutions, please go to: www.maximintegrated.com/mri.

Static Magnetic Field

MRI imaging requires the patient to be placed in a strong magnetic field in order to align the hydrogen nuclei. There are typically three methods to generate this field: fixed magnets, resistive magnets (current passing through a traditional coil of wire), and super-conducting magnets. Fixed magnets and resistive magnets are generally restricted to field strengths below 0.4T and cannot generate the higher field strengths typically necessary for high-resolution imaging. As a result, most high-resolution imaging systems use super-conducting magnets. The super-conducting magnets are large and complex; they need the coils to be soaked in liquid Helium to reduce their temperature to a value close to absolute zero.

The magnetic fields generated by these methods must not only be strong, but also highly uniform in space and stable in time. A typical system must have less than 10ppm variation over the imaging area. To achieve this accuracy, most systems generate weaker static magnetic fields using specialized shim coils to "shim" or "tweak" the static field from the super conductor and thereby correct for field inaccuracies.

Gradient Coils

To produce an image, the MRI system must first stimulate hydrogen nuclei in a specific 2D image plane in the body, and then determine the location of those nuclei within that plane as they precess back to their static state. These two tasks are accomplished using gradient coils which cause the magnetic field within a localized area to vary linearly as a function of spatial location. As a result, the resonant frequencies of the hydrogen nuclei are spatially dependent within the gradient. Varying the frequency of the excitation pulses controls the area in the body that is to be stimulated. The location of the stimulated nuclei as they precess back to their static state can also be determined by using the emitted resonant RF-frequency and phase information.

An MRI system must have x, y, and z gradient coils to produce gradients in three dimensions and thereby create an image slice over any plane within the patient's body. The application of each gradient field and the excitation pulses must be properly sequenced, or timed, to allow the collection of an image data set. By applying a gradient in the z direction, for example, one can change the resonant frequency required to excite a 2D slice in that plane. Therefore, the spatial location of the 2D plane to be imaged is controlled by changing the excitation frequency. After the excitation sequence is complete, another properly applied gradient in the x direction can be used to spatially change the resonant frequency of the nuclei as they return to their static position. The frequency information of this signal can then be used to locate the position of the nuclei in the x direction. Similarly, a gradient field properly applied in the y direction can be used to spatially change the phase of the resonant signals and, hence, be used to detect the location of the nuclei in the y direction. By properly applying gradient and RF-excitation signals in the proper sequence and at the proper frequency, the MRI system maps out a 3-D section of the body.

To achieve adequate image quality and frame rates, the gradient coils in the MRI imaging system must rapidly change the strong static magnetic field by approximately 5% in the area of interest. High-voltage (operating at a few kilovolts) and high-current (100s of amps) power electronics are required to drive these gradient coils. Notwithstanding the large power requirements, low noise and stability are key performance metrics since any ripple in the coil current causes noise in the subsequent RF pickup. That noise directly affects the integrity of the images.



To differentiate tissue types, the MRI systems analyze the magnitude of the received signals. Excited nuclei continue to radiate a signal until the energy absorbed during the excitation phase has been released. The time constant of these exponentially decaying signals ranges from tens of milliseconds to over a second; the recovery time is a function of field strength and the type of tissue. It is the variations in this time constant that allow different tissue types to be identified.

Transmit/Receive Coils

Transmit and receive coils are used both to stimulate the hydrogen nuclei and to receive the signals generated as the nuclei recover. These coils must be optimized for the particular body area to be imaged, so they are available in a wide variety of configurations. Depending on the area of the body to be imaged, either separate transmit and receive coils or combined transmit/receive coils are used. In addition, to improve image acquisition times, MRI systems use multiple transmit/receive coils to recover more information in parallel, thus utilizing the spatial information associated with the location of the coils.

RF Receiver

An RF receiver is used to process the signals from the receiver coils. Most modern MRI systems have six or more receivers to process the signals from multiple coils. The signals range from approximately 1MHz to 300MHz, with the frequency range highly dependent on applied-static magnetic field strength. The bandwidth of the received signal is small, typically less than 20kHz, and dependent on the magnitude of the gradient field.

A traditional MRI receiver configuration has a low-noise amplifier (LNA) followed by a mixer. The mixer mixes the signal of interest to a low-frequency IF frequency for conversion by a high-resolution, low-speed, 12-bit to 16-bit analog-to-digital converter (ADC). In this receive architecture, the ADCs used have relatively low sample rates below 1MHz. Because of the low-bandwidth requirements, ADCs with higher 1MHz to 5MHz sample rates can be used to convert multiple channels by time-multiplexing the receive channels through an analog multiplexer into a single ADC.

With the advent of higher-performance ADCs, newer receiver architectures are now possible. High-input-bandwidth, high-resolution, 12-bit to 16-bit ADCs with samples rates up to 100MHz can also be used to directly sample the signals, thereby eliminating the need for analog mixers in the receive chain.

Transmitter

The MRI transmitter generates the RF pulses necessary to resonate the hydrogen nuclei. The range of frequencies in the transmit excitation pulse and the magnitude of the gradient field determine the width of the image slice. A typical transmit pulse will produce an output signal with a relatively narrow ± 1 kHz bandwidth. The time-domain waveform required to produce this narrow frequency band typically resembles a traditional sinc function. This waveform is usually generated digitally at baseband and then upconverted by a mixer to the appropriate center frequency. Traditional transmit implementations require relatively low-speed digital-to-analog converters (DACs) to generate the baseband waveform, as the bandwidth of this signal is relatively small.

Again, with recent advances in DAC technology other potential transmit architectures are achievable. Very-high-speed, high-resolution DACs can be utilized for direct RF generation of transmit pulses up to 300MHz. Waveform generation and upconversion over a broad band of frequencies can, therefore, now be accomplished in the digital domain.

Image Signal Processing

Both frequency and phase data are collected in what is commonly referred to as the k-space. A two-dimensional Fourier transform of this k-space is computed by a display processor/computer to produce a gray-scale image.

Related Parts		
MAX19526	Ultra-Low-Power, 8-Channel, 12-Bit, 40Msps ADC	Free Samples
MAX19527	Ultra-Low-Power, Octal, 12-Bit, 50Msps, 1.8V ADC with Serial LVDS Outputs	Free Samples
MAX19528	Ultra-Low-Power, 8-Channel, 12-Bit, 64Msps ADC	Free Samples
MAX19588	High-Dynamic-Range, 16-Bit, 100Msps ADC with -82dBFS Noise Floor	Free Samples
MAX19681	12-Bit, 1.5Gsps High-Dynamic Performance DAC	

More Information

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