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Cost effective power amplifiers for pulsed NMR sensors

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Abstract: Sensors that measure magnetic resonance relaxation times are increasingly finding applications in areas such as food and drink authenticity and waste water treatment control. Modern permanent magnets are used to provide the static magnetic field in many commercial instruments and advances in electronics, such as field programmable gate arrays, have provided lower cost console electronics for generating and detecting the pulse sequence. One area that still remains prohibitively expensive for many sensor applications of pulsed NMR is the requirement for a high frequency power amplifier. With many permanent magnet sensors providing a magnetic field in the 0.25T to 0.5T range, a power amplifier that operates in the 10MHz to 20MHz rage is required. In this work we demonstrate that some low cost commercial amplifiers can be used, with minor modification, to operate as pulsed NMR power amplifiers. We demonstrate two amplifier systems, one medium power that can be constructed for less than Euro 100 and a second much high power system that produces comparable results to commercial pulse amplifiers that are an order of magnitude more expensive. Data is presented using both the commercial NMR MOUSE and a permanent magnet system used for monitoring the clog state of constructed wetlands.

Keywords: magnetic resonance; pulsed NMR; relaxation time; power amplifier.

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1. Introduction

High frequency (HF) is the International Telecommunication Union designation for the range of radio frequency electromagnetic waves between 3MHz and 30MHz. Protons have a gyromagnetic ratio of 42.58 MHz/T and so for magnetic resonance applications, the HF frequency range corresponds to magnetic fields of between 0.07T and 0.7T. The advancement of permanent magnet technology has seen numerous reports of research instruments and a range of commercial products appear on the market that use permanent magnets to produce the uniform static magnetic field for applications in magnetic resonance relaxation time measurements. Examples include single sided or unilateral systems such as the profile NMR-MOUSE [1,2], benchtop MRI systems using magnets in a Halbach arrangement [2,3] and simple sensors using a pair of magnets to define the sensitive region [4-6]. The electronics used to collect the MRI signal is often referred to in the literature as a console. These consist of the generation of the HF pulse sequence, a power amplifier, a duplexer to isolate the high power input signal to the coil from the very small return MR signal and the detection circuit. Commercial consoles are typically several thousands of Euro/Dollars and one of the most expensive parts of the console is the power amplifier. However, parts of the HF spectrum are licensed for used by amateur radio enthusiasts for private recreation and non-commercial exchange of messages and as such low cost commercial amplifiers are produced for this application. In this work we report how two low cost HF amplifiers can be modified for use in pulsed magnetic resonance applications and demonstrate their use for relaxation time measurements using both commercial and homemade permanent magnet based sensors.

Figure 1. (**a**) Modified KL203 with relay removed. (**b**) Modified KL405 with relay removed. (**c**) Operational amplifier based on LT1222.

2. Experimental Section

The commercial HF amplifiers identified for this work were from the product range of RM Costruzioni Elettroniche (rmItaly.com). The amplifiers were the KL203 (~60 Euro) [7] and the KL405 (~200 Euro) [8] with each amplifier having both transmit and receive circuitry and the switching between initiated using a rely. For our application the amplifiers required the relay to be removed and solid links placed to set the amplifiers for transmit only operation (Figure 1a and 1b). The input power required to operate these amplifiers are 0.5W and 1W respectively which is significantly more than a commercial NMR spectrometer would produce. Whilst at first sight this may appear a problem it actually provides a significant advantage as it acts as gating mechanism to reduce leakage but does

require an additional amplifier between spectrometer and RM amplifier. For the KL203, a simple inverting operational amplifier was constructed using the Linear Technology LT1222 [9] with a 390Ω input resistor and 3.9kΩ feedback resistor (Figure 1c). The gain bandwidth product for the LT1222 is 500MHz however it must be used with a minimum gain of ten giving a bandwidth of 50MHz. HF amplifiers are usually designed to run from 12V-14V batteries so the supply to the LT1222 was provided by two TRACOPOWER TSR 1-24120 dc/dc converters [10] giving plus and minus 12 V supplies. The NMR spectrometer used in this work was a Tecmag (Houston, TX) Apollo using a standard CPMG sequence [11] with the 180° pulse set to be twice the length of the 90° pulse rather than twice the amplitude and the same length. For the higher power KL405, a simple operational amplifier circuit was not found sufficient to deliver the input power required and so a commercial HF amplifier Henry Radio 20B (US$425) with a bandwidth from 1.8MHz to 30MHz, was used with 15dB fixed attenuation of the input signal. A very weak NMR signal could be obtained with the Henry Radio 20B alone but this was not sufficient for reliable measurements. When the output of the Henry Radio 20B is used to drive the KL405, it produced power delivery to the sample with a similar optimum 90^o pulse length to that produced by the NMR power amplifier on the Magritek Kea2 spectrometer [2] as described below.

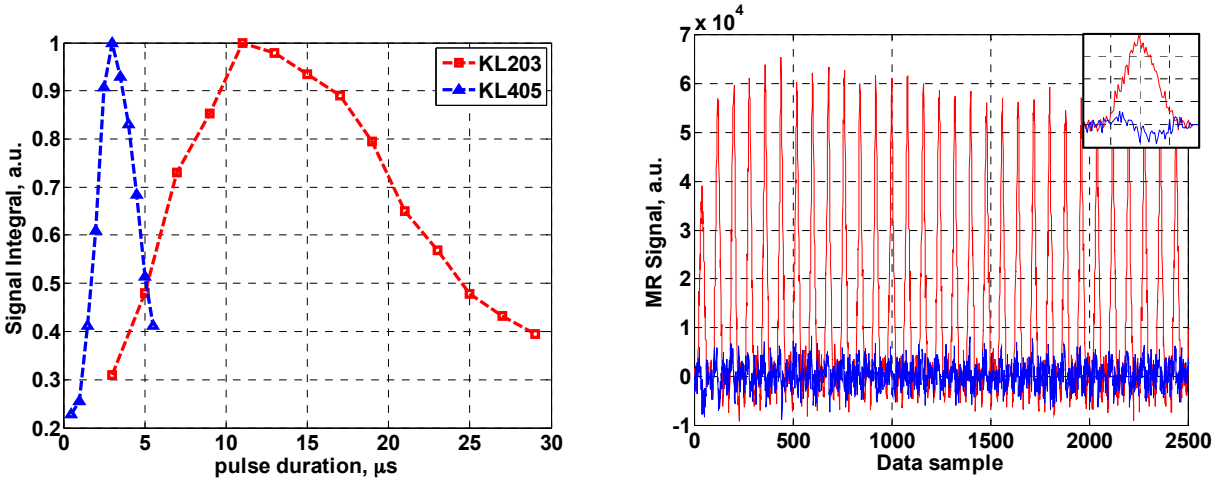
Two different magnetic resonance systems were used in these experiments, a NMR profile MOUSE [1,2] and permanent magnet system used for monitoring the clog state of constructed wetlands [4,12]. The MOUSE is a unilateral system with a sensitive region just above the surface for which one of the original intensions was assessing the age of rubber in vehicle tires. The wetlands probe design is a bore-whole configuration where a solenoid in the region between two disc magnets is used to probe the sample. The NMR MOUSE® operates at 10.64MHz, and the wetlands probe operates at 11.5MHz. Only data collected on the MOUSE using the LT1222/KL203 and on the constructed wetland sensor using the Henry/KL405 (excluding the find 90) are presented however both system work with both amplifier arrangements.

3. Results and Discussion

In Figure 2a we show the results of a 90° pulse calibration sequence that runs a CPMG sequence and finds the integral of the echoes as the length of the 90^o pulse length is increased. This should rise, giving the optimum value at the peak, and then fall again. The shorter the optimum 90^o pulse length, the greater the power that is being delivered into the sample. It therefore represents a measure of the output power of the amplifier. The actual power delivered will however also depend upon the matching to 50Ω at the resonant frequency. For the LT1222/KL203 (squares in Figure 3) the optimum value is 11μs and for the Henry/KL405 (triangles in Figure 3) the optimum is 3μs with both using the NMR MOUSE with an olive oil sample. For comparison, a Kea2 spectrometer using its own 100W power amplifier and driving the NMR MOUSE had an optimum 90^o pulse length of 4.4μs. Figure 2b shows a typical set of echoes resulting from the CPMG sequence using the LT1222/KL203. In Figure 3 we show the result of the same CPMG sequence taken on the MOUSE using the LT1222/KL203 with a sample of old rubber (left) and a sample of new rubber (right); old in this context means that it was of sufficient age to be hard and brittle. This data was taken using 32 echoes and 2048 averages.

The graphs show the decay in height of the echoes is significantly faster for the old rubber sample which indicates a much shorter T_2^{eff} for the old rubber than the new rubber as previously reported [13].

Having demonstrated the ability of the low power system, we show the ability to measure the spin-lattice relaxation time using the Henry/KL405 amplifier and the constructed wetland sensor. Syringes were prepared with 100% glycerol and glycerol/water mixtures of 80/20, 60/40, 40/60 and 20/80 and a saturation recovery method, where the inter-experimental repetition time was varied and plotted against the signal intensity, was used to acquire the T_1 relaxation time for each of the samples [14]. Figure 4a shows a typical set of data which is taken for the 100% glycerol sample. The value of T_1 is expected to fall exponentially with the increasing percentage of water in the sample and this can be seen in Figure 4b and are in good agreement with the available literature [15].



(a) (b)

Figure 2. (**a**) Signal intensity against 90° pulse length for the KL203 (squares) and the KL405 (triangles) using the NMR MOUSE and an olive oil sample. (**b**) Typical echo train from CPMG sequence on NMR MOUSE® using KL203 with olive oil sample. Insert shows close up of the first echo demonstrating the relationship between the two signal components.

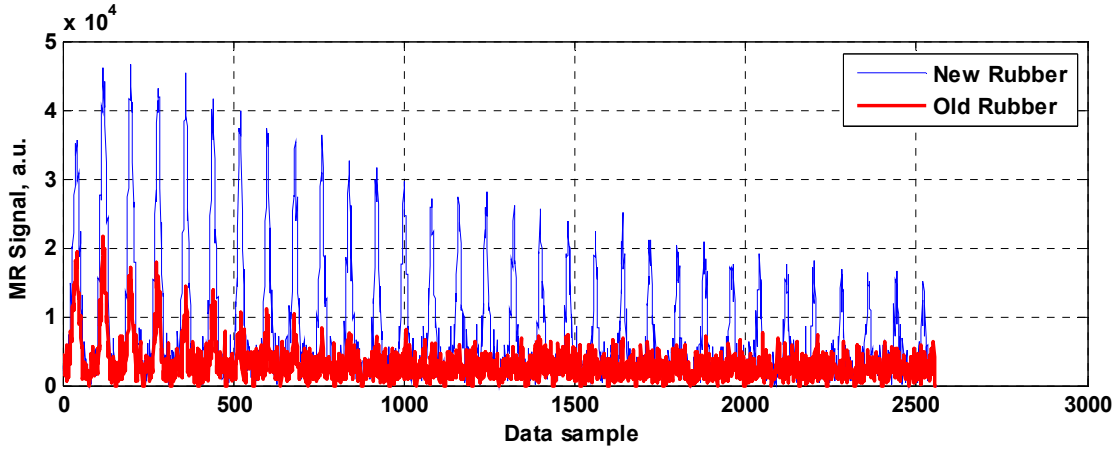


Figure 3. Typical echo trains from the CPMG sequence on NMR MOUSE® using KL203 with new (blue thin line) and old (red and thick) rubber samples.

It should be noted that there are limits to the range over which the Henry/KL405 combination can be used; if there is a combination of a repetition time that is too small and the number of echoes too large then noise is observed in the final echoes. Such a limitation does not restrict the measurement of most T_1 and T_2^{eff} values that would be required in sensor applications. No such limiting factor was observed for the LT1222/KL203 combination.

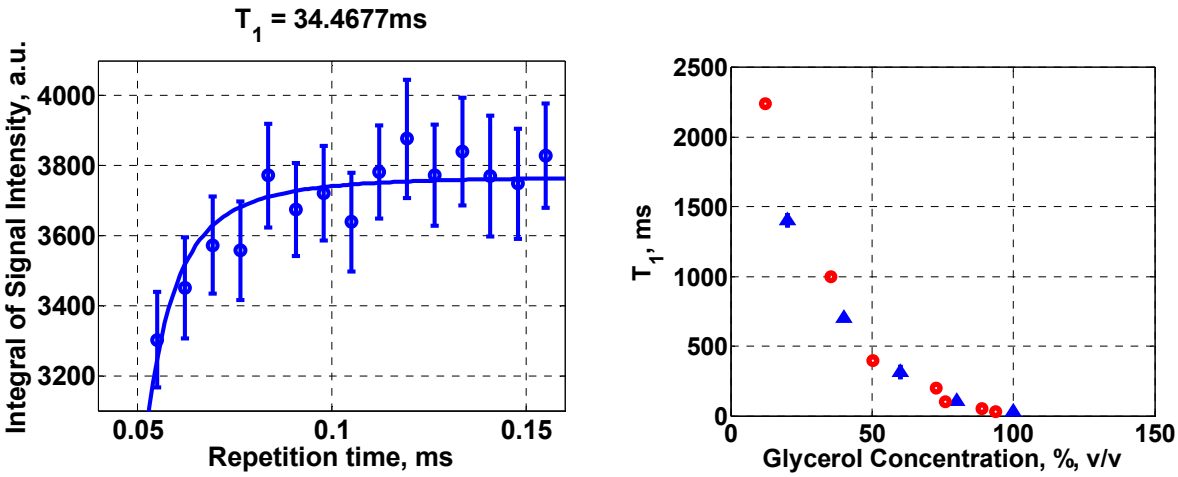


Figure 4. (a) Repetition time T_1 buildup using the wetland probe and Henry/KL405 for a glycerol sample. (**b**) The measured T_1 values as a function of percentage glycerol (in water) concentrations (triangles) with book values from [15] (circles). Error bars are shown with the triangles in (b) but are too small to be visible on most points.

4. Conclusions

We have demonstrated in this work that HF amplifiers can provide a viable alternative to commercial NMR power amplifiers for sensor applications of pulsed NMR. The ability to measure T_2^{eff} and T_1 (using saturation recovery) have been demonstrated using two different systems, one unilateral and one traditional bore style magnet arrangements. Whilst the increasing availability of low cost permanent magnets offer relaxation time measurement as a viable sensor technique, the cost of the electronics involved must also fall to make this a commercial reality. The use of the amplifiers reported here make this a step closer.

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Author Contributions

All authors contributed to the experimental work and the writing of the article.

Conflicts of Interest

The authors declare no conflict of interest.

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