

RF probe recovery time reduction with a novel active ringing suppression circuit

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Abstract

A simple Q -damper device for active probe recovery time reduction is introduced along with a straightforward technique for the circuit's component value optimization. The device is inductively coupled to a probe through a coupling transformer positioned away from the main coil, which makes the design independent of the coil type being used. The Q -damper is a tuned circuit, which is resonant at the same frequency as the probe and can be actively interrupted. When the circuit is interrupted, it is detuned and, thereby, is uncoupled from the probe, which operates normally. Turning the device on leads to re-coupling of the circuits and causes splitting of the probe's resonance line, which can be observed through its drive port. A resistance of an appropriate value is introduced into the Q -damper circuit, resulting in smoothing of the resonance splitting into one broad line, representing the coupled system's low- Q state, in which the energy stored in the main coil is efficiently dissipated. The circuit's component values are optimized by monitoring the shape of this low- Q state. Probe recovery time reduction by, approximately, an order of magnitude has been obtained with this device. Application of the device during an NQR experiment led to an increase in the signal-to-noise ratio by a factor of 4.9.

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1. Introduction

One of the central issues in nuclear magnetic resonance (NMR), magnetic resonance imaging (MRI), and nuclear quadrupole resonance (NQR) is increasing the signal-to-noise ratio (SNR) of signals. A relatively straightforward way to achieve this is to maximize the quality factor, Q , of the receiver coil used to acquire the signal, since the SNR is proportional to \sqrt{Q} . In high frequency MRI studies, losses in the samples generally dominate, and the Q factor of sample-loaded coils cannot be increased beyond a certain value. On the other hand, in low frequency investigations, such as laser-po-

larized noble gas MRI studies [1], industrial process and quality control by permanent magnet NMR [2] or ^{14}N -based illicit substance detection by NQR [3], the sample losses are insignificant compared to the losses in the coils themselves and, therefore, high sample-loaded coil Q factors can be obtained by alterations in the design. This approach to improving the SNR, unfortunately, is associated with some serious difficulties. One of the drawbacks of increasing Q as much as possible is the inability to register broad signals. This may occur at low frequencies (on the order of several megahertz) when signal linewidths become comparable to the bandwidth of the coil, which is proportional to ω_0/Q , where ω_0 is the coil's resonance frequency. At higher frequencies, this limitation may also play a role for devices with very high Q factors, such as superconducting surface

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coils [4]. This condition, however, is not reached in most experiments. A much more important limiting factor is the increase in the coil's recovery time as the Q is raised. This occurs due to lowering of the internal losses in the coil, such that the energy stored in it during transmission is dissipated slowly, resulting in subsequent “ringing,” during which signal detection is impossible. The significance of the current work is in the proposed means of overcoming this limitation.

Following transmission, the energy stored in a coil dissipates over a period of time, during which ringing takes place at the coil's resonance frequency. This “ring-down” period is equal to approximately 20 time constants, τ_r , and has the following form [5]:

$$\tau_r = 2Q/\omega_0. \quad (1)$$

The inverse proportionality to resonance frequency accounts for a greater importance of this effect in low frequency studies. The ringing voltage in coils with even moderately high Q factors may overwhelm the signal coming from a sample for hundreds of microseconds and result in a loss of a large fraction of the signal. In wide-line studies, the rapidly decaying signals may actually become undetectable before the acquisition can begin. It is, therefore, desirable to get rid of the energy stored in the coil after a transmission pulse as fast as possible and begin acquisition before the signal has decayed. When multi-pulse sequences are utilized, there are additional advantages of being able to detect signal sooner after transmission and, therefore, decrease spacing between pulses. In the spin-locked spin-echo sequence (SLSE) [6–8], when the inter-pulse spacing, τ , is much shorter than the T_2 relaxation time, the spin-locking condition is achieved, resulting in a spin-echo train that decays with a longer relaxation time constant that approaches $T_{1\rho}$ in the $\tau \rightarrow 0$ limit, rather than with T_2 , as in the single-shot or spin-echo type experiments. This permits longer signal acquisitions per pulse train, resulting in higher SNR. In the steady-state, free precession sequence (SSFP) used in NMR [9], and its variations applied in NQR, the strong off-resonance comb (SORC) [10–12] and the transmission on—reception off (TONROF) [13], the time τ is commonly set to be less than the T_2 , which leads to the steady-state condition. When this condition is fulfilled, the signal amplitude in each acquisition window between pulses is strongly augmented if the pulse spacing is reduced. Additionally, more acquisition windows become available during the same total experimental time, resulting in an additional SNR advantage. In this manuscript, we provide an example of this effect, which allowed achieving a factor of 4.9 SNR improvement by utilizing our Q -damping device.

A number of methods attempting to circumvent the problem of coil ringing have been proposed. Among them are techniques that do not require alterations in the probe circuits, such as using a short phase-inverted

pulse following the main RF pulse [14] or achieving a compromise between the SNR and the probe recovery time by “overcoupling” the probe to the receiver [15–17]. The former method has limited application due to its complexity (timing and probe tuning need to be very accurate). The latter technique relies on the fact that the preamplifier is “noise-matched” and not necessarily “impedance-matched” to the 50 Ω coil impedance to maximize the SNR. A high input resistance preamplifier is utilized to reduce the effective “loaded” Q of the coil. The method is easy to apply if such a preamplifier is available; however, the reduction in the ringdown time is relatively small (a factor of 5 reduction has been achieved).

It is important to point out that a further increase in ringdown time may occur when a passive quarter-wavelength transmit/receive (T/R) switching circuit is used [18] in experiments during which no Q -damping is undertaken or in conjunction with an overcoupling technique mentioned above. In this configuration, the preamplifier protection cross diodes and the transmitter amplifier isolation cross diodes need to be well balanced. If during the decay of the ringing voltage, the transmitter amplifier becomes isolated first, while the preamplifier protection cross diodes are still shorted, high impedance is created at the probe, which is, thereby, isolated from both the transmitter and the receiver. Ringing then occurs for a longer period governed by the coil's higher “unloaded” Q factor (two times the Q factor of the coil “loaded” with 50 Ω [16] and even greater in the case of the overcoupling schemes) until the ringing voltage drops sufficiently for the coil to become coupled to the receiver circuit. Even for well-balanced diodes, until the ringing voltage decays sufficiently for the diodes to switch off, the probe is coupled to the 50 Ω transmitter, not the receiver, thereby invalidating the overcoupling techniques for this part. The use of an active T/R switch helps alleviate this problem.

Existing active Q -damping techniques involve switching the coil's Q to a lower value during a short time period immediately following the transmitter pulse. When the energy stored in the coil is dissipated, the Q is switched back to its original value permitting signal detection with high SNR. In these techniques, generally, some sort of an actively controlled Q -damping circuit is coupled to the coil for the period of the stored energy dissipation. Approximately fivefold reductions in ringdown time have been achieved with some relatively simple circuits [5,19]. Better results have also been obtained at the cost of significant increase in complexity [20].

The goal of the current study was to develop an active Q -damping technique that could be easily applied to a variety of coils, and to work out a system of adjusting circuit component values that would lead to maximal reduction in the ringdown time. In this work, we introduce a new relatively simple Q -damping circuit that

permits reduction of the ringdown time by, roughly, an order of magnitude, along with a method of optimizing the circuit's parameters using any common return-loss meter utilized for probe tuning. The application of the circuit is not limited to any specific type of coil, and can be used as much with a solenoid as with, for example, a birdcage coil.

2. Circuit schematic

Since the energy stored in a coil after transmission is to be dissipated by lowering the Q only for a brief period of time, the circuit was designed to be coupled and uncoupled from the probe by a fast logic-controlled switch. Additionally, the coupling scheme was selected with some care. Since switching is controlled by DC voltages, the probe coil and the Q -damper were coupled inductively, using a small air-core transformer in a convenient location away from the coil. This helped prevent charging the probe circuit's capacitors by the DC control currents, which could create new impulse-response ringing upon discharging, after the Q -damper is turned off.

The circuit schematic is presented in Fig. 1. We utilized a common inductively driven transmit/receive

probe (shown on the right-hand side), which was coupled via a coupling transformer to the Q -damper. The latter was a tuned circuit resonating at the same frequency as the probe. Details of the design and the methodology of the component value optimization are described below. When the Q -damper is switched off by effectively interrupting the circuit, the secondary coil of the transformer connected to it carries no current. In this state, the primary coil of the transformer, which is connected in series with the main circuit, conserves all of the introduced RF energy, and the transformer can be represented as a small inductance, which is insignificant compared to the inductance of the main coil. In the "on" state, the Q -damper is coupled to the main circuit, and the secondary coil of the transformer efficiently absorbs energy from the probe. Control is performed with TTL logic provided by the spectrometer, amplified to a 12 V DC level, governing the on/off switching of the metal oxide semiconductor field effect transistors (MOSFETs), which were chosen due to their superior properties when used as electrically isolated logic-controlled switches. When logic "0" is presented by the spectrometer, no current flows through the 10 K resistors and the voltage of 35 V appears at the points (1) and (2) indicated in the figure. This voltage lifts the

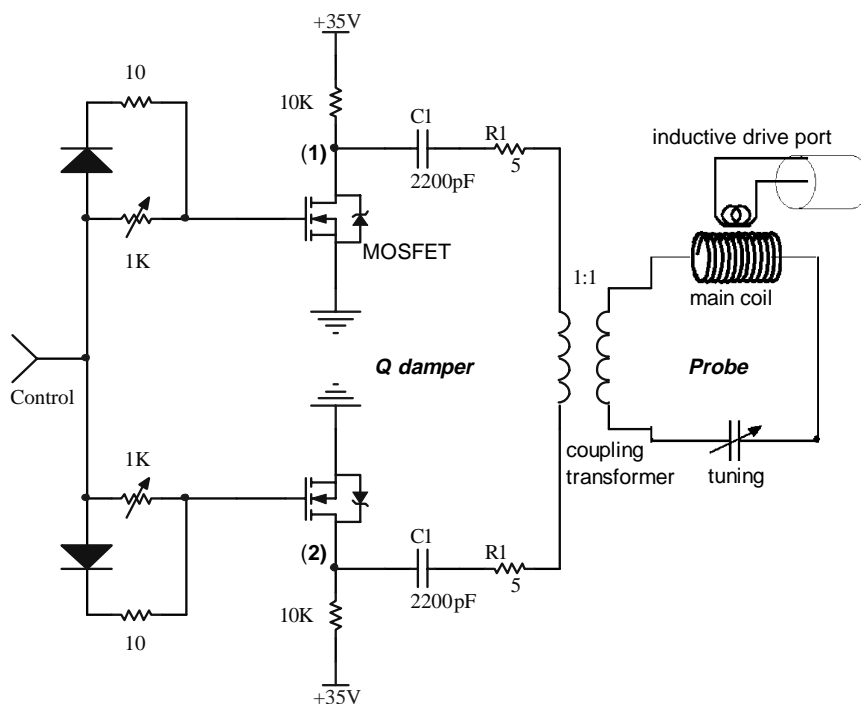


Fig. 1. Schematic of the Q -damper circuit coupled to the probe via a coupling transformer is presented. The probe is of a conventional design with an inductively driven main solenoid coil. The Q -damper is a tuned circuit resonating at the same frequency as the probe (using C1 capacitors). MOSFET transistors are used as logic-controlled gates, managed by a TTL signal converted to a 12 V level (logic "1") and 0 V (logic "0"). The diodes and the 1 K variable resistors are used to shape the control pulses for optimal performance. Points (1) and (2) are placed at 35 V in the "off" state during logic "0" to lift the RF coming from the probe above ground and prevent conduction through the MOSFET-associated Zener diodes. The device in this state is detuned. During logic "1" the points (1) and (2) are both connected to ground (and, thereby, to each other), which tunes the Q -damper and couples it to the probe through the coupling transformer. Symmetry of the device allows for the ground connection without affecting performance. Resistors R1 are used to spoil the Q of this coupled system to permit efficient dissipation of the energy stored in the main coil after a transmission pulse.

RF, which is coming from the probe during a transmit pulse via the coupling transformer, above zero voltage level, removing the paths to ground through the associated Zener diodes of the MOSFETs. The MOSFETs are, thereby, turned off and appear as open circuits. The Q -damper in this state is interrupted and uncoupled from the main coil. When logic “1” is presented, on the other hand, the MOSFETs conduct, and the points (1) and (2) become effectively connected to ground and to each other. Thus, the Q -damper circuit becomes tuned and coupled to the main coil. The symmetry of the component arrangement (resistors and capacitors) in the Q -damper permits the ground connection at the center point without influencing its RF properties. Additionally, because of the circuit’s symmetry, the points (1) and (2) always remain at the same potential, independently of the state of the device. This helps prevent currents in the secondary transformer coil during the switching process, which could, otherwise, become an alternative

source of ringing in the main coil. To utilize the Q -damper during experiments, the logic “0” is presented during the RF transmission and the signal acquisition (when the probe needs to be operational), while the logic “1” is supplied during short periods following the transmission pulses, during which the energy stored in the main coil becomes dissipated.

3. Results and discussion

3.1. Component value optimization

Our Q -damper is a tuned circuit, which is resonant at the same frequency as the probe and can be actively coupled to or decoupled from it. It is well known that when two resonators tuned to the same frequency are coupled, two modes are formed at the frequencies situated below and above the original resonance frequency,

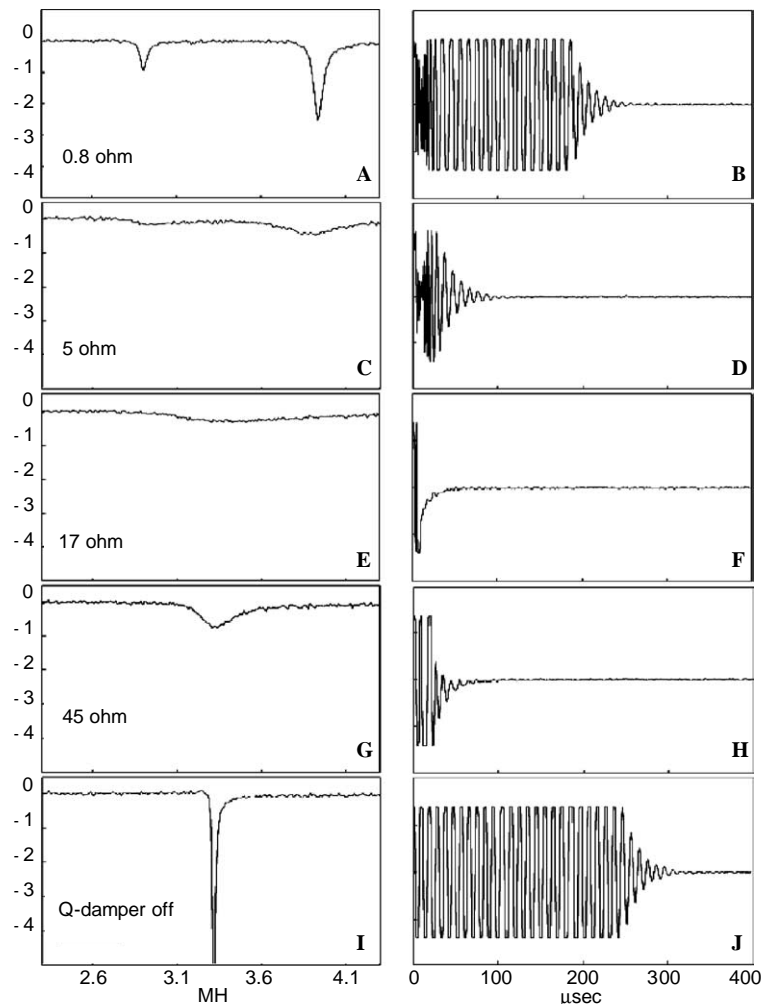


Fig. 2. Results of the coupled Q -damper-probe system’s return loss measurements performed through the probe’s driving port are shown on the left-hand side for the cases of the (A and B) below optimal introduced resistance, the (C) optimal resistance and the (D and E) above optimal resistance. Associated probe ringing patterns are displayed on the right-hand side for each case (F–J). Logic “1” was supplied to the MOSFETs for 30 μ s after transmission pulses, replaced by logic “0” during all other times.

corresponding to the currents flowing in the same and the opposite sense in the two circuits. Thus, if a return loss measurement is performed at the probe's connection port when the coupling is initiated, two peaks will appear in place of the previously observed one probe's resonance peak, more or less symmetrically positioned with respect to it. The distance between the peaks depends on the strength of the coupling (mutual inductance of the primary and the secondary coupling transformer coils in our case). The Q factor of this coupled system can be spoiled by introducing resistance into one of the circuits (the Q -damper circuit is obviously a better choice). The rate of the dissipation of the energy stored in the main coil during this low- Q state depends on the value of this resistance.

Fig. 2 serves to illustrate the method of resistance optimization and shows the results of ringing pattern measurements, corresponding to different introduced resistance values. The Q -damper was turned on after the transmission pulse for a period of 30 μ s in all cases. When the resistance is smaller than the optimal value, two peaks are resolved (Figs. 2A and B; corresponding ringing patterns—Figs. 2F and G). When the resistance becomes larger than the optimal value, the Q -damper begins to turn off and the circuits become decoupled, approaching the original condition in which no Q -damper is present (Figs. 2D and E; corresponding ringing patterns—Figs. 2I and J). Neither of these situations is optimal for minimizing the ringdown time. In the former case, the ringing proceeds at two ringing frequencies simultaneously, in the latter it occurs at the original resonance frequency, and in neither case is the energy efficiently dissipated. An optimal resistor value (17 Ω , in our case), on the other hand, leads to broadening of the two peaks, such that they become combined into one very broad and shallow band (Fig. 2C). This is the condition of the lowest Q factor for the system, in which the energy is dissipated very quickly. Fig. 2H shows the measured ringing pattern for this case. The trend observed in Fig. 2 is presented in greater detail in Fig. 3, which shows the dependence of the ringdown time on the introduced resistance. Interestingly, the data points collected near the minimum of this curve show almost no change in the ringdown time for a range of resistances. This feature is probably observed due to the fact that the actual probe ringing obtained with these values becomes so short that the ringing in the rest of the equipment dominates. The 4-coefficient polynomial function fit to the data shown in the figure provides a means of roughly estimating the minimum ringdown time of the probe, which occurred when a 17 Ω resistance was introduced and had a value of approximately 23 μ s. This represents a ballpark recovery time reduction by an order of magnitude, as compared with the case of 350 μ s ringdown time obtained with the disabled Q -damper.

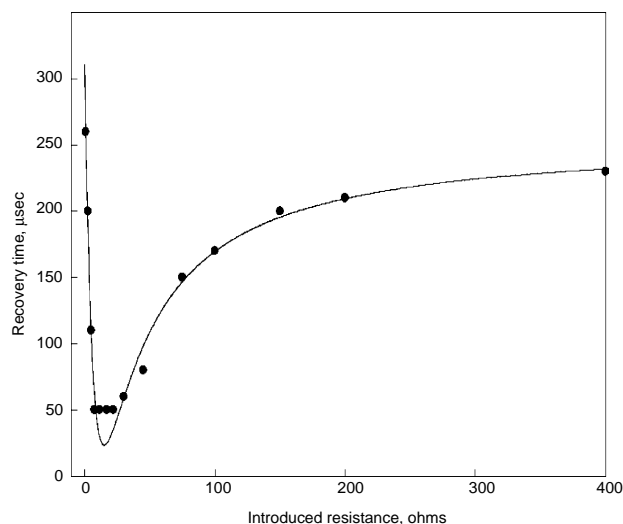


Fig. 3. The dependence of the ringdown time on the value of introduced resistance is presented. The flat region near the minimum of the curve probably signifies the domination of the probe's ringing by the ringing in the rest of the spectrometer and the transmit/receive switching system. The 4-coefficient polynomial function fit to the data permits estimating the minimum of the probe's ringdown time (approximately 23 μ s), representing a ballpark reduction by an order of magnitude, as compared with the case of 350 μ s ringing observed with the disabled Q -damper.

3.2. Experimental evaluation: the SNR advantage

The Q -damper's utility has been demonstrated with a single-shot pulse sequence using a sample of hexamethylenetetramine ($C_6H_{12}N_4$, ν -transition, 3.31 MHz). The results are presented in Fig. 4. In Fig. 4A, the device was turned on after the transmission pulse for a period of 30 μ s, during which time the energy accumulated in the probe was removed. The Q -damper was subsequently turned off to permit acquisition of the signal. Fig. 4B shows the results of conducting the measurement with the Q -damper permanently disabled. Comparing the figures shows that using the device allowed registering the portion of the signal between approximately 50 and 350 μ s that would otherwise be overwhelmed by ringing.

To demonstrate the SNR advantages offered by the Q -damper, we have conducted a series of NQR experiments with the same sample using the TONROF pulse sequence. Application of the Q -damper led to a reduction of the probe's recovery time, permitting closer positioning of the pulses in the sequence. As was mentioned in Section 1, in this type of a multi-pulse sequence the signal amplitude in each acquisition window between pulses is augmented when the pulse spacing is reduced. Also, more acquisition windows become available during the same total experimental time. Both of these effects contributed to SNR improvements, as demonstrated in Fig. 5 in the form of the dependence of the obtained SNR on the probe's recovery time. The SNR of 27 was obtained when the Q -damper was

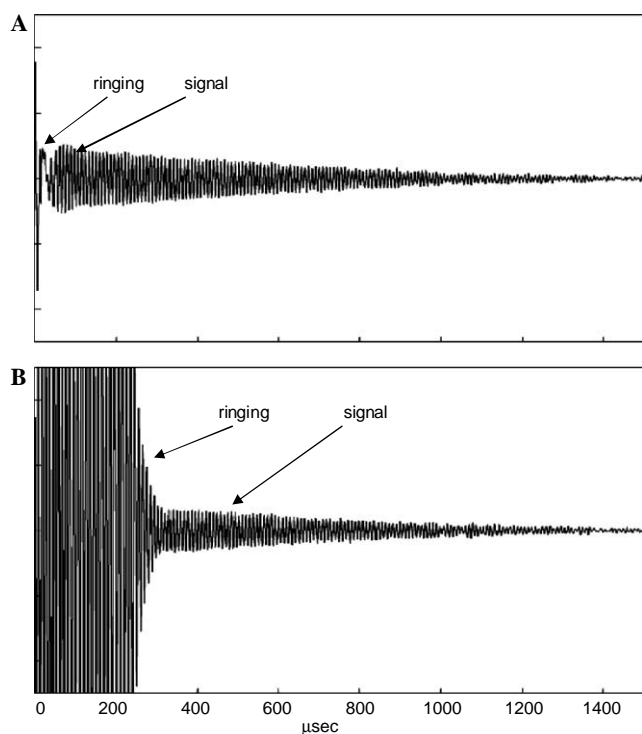


Fig. 4. Signals resulting from single-shot experiments with hexamethylenetetramine ($C_6H_{12}N_4$, ν -transition, 3.31 MHz) are presented in the presence of the optimized Q -damper (A) and with the Q -damper disabled (B). Acquisition was started immediately after the transmission pulse in order to show both the ringing and the sample signal. The Q -damper was turned on after transmission for a period of 30 μ s (A), during which the energy accumulated in the probe was removed. Comparing the two parts of the figure shows that the use of the device permits starting to acquire the signal much earlier.

turned off and the probe's recovery time was, therefore, 350 μ s. The pulse train consisted of 17 pulses separated by the ringdown time and the acquisition period, which was set to 32 μ s in all cases (pulse width was 25 μ s; total experimental time was 7 ms). Applying the Q -damper led to changes in the ringdown time and permitted closer positioning of the pulses. Thus, for the optimized case, the ringdown time was restricted to 50 μ s and the pulse train consisted of 64 pulses, occupying the same total experimental time as before. The SNR of 132 was obtained for this case, representing a factor of 4.9 improvement resulting from the use of the Q -damper.

3.3. Experimental

All experiments, including the recording of the ringing patterns as well as the NQR signal detection, were conducted with a low frequency (1–10 MHz) one-channel NQR spectrometer system constructed by Spinlock (Cordoba, Argentina). A common RF probe design was utilized with a 300 ml inductively coupled solenoid coil. Isolation diodes used in transmit/receive switching circuitry were manufactured by Motorola (Schaumburg, IL, USA, model 1N4148). The MOSFET transistors

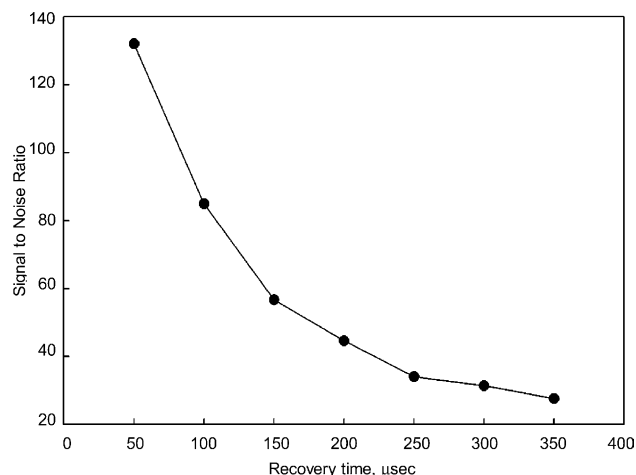


Fig. 5. SNR advantages realized due to the ability to begin earlier acquisition of the signal are demonstrated in the form of the dependence of the SNR on the probe's recovery time during a TONROF experiment. The enhancement occurs because of the augmentation of the signal in each of the acquisition windows occurring between the pulses and due to the availability of a greater number of such windows during the same experimental time, when the probe's recovery time is reduced by the application of the Q -damper. The SNR enhancement by a factor of 4.9 was obtained for the case of the 50 μ s recovery time (optimized Q -damper), as compared with the case of the 350 μ s recovery time (Q -damper disabled).

utilized as logic-controlled switching elements were produced by International Rectifier (El Segundo, CA, USA, model IRFP450). The return loss measurements were conducted using a Rohde & Schwarz 9 kHz–4 GHz vector network analyzer (München, Germany, model ZVRE). A 100 g sample of hexamethylenetetramine ($C_6H_{12}N_4$, ν -transition, 3.31 MHz) purchased from Anedra (San Fernando, Argentina) was used in all NQR experiments.

4. Conclusions

Drastic probe recovery time reduction was achieved with a novel active ringing suppression circuit, inductively coupled to the main coil with a conveniently positioned low inductance series transformer. A robust method of the circuit's component value optimization was developed to maximize the Q -damper's efficiency. The basic steps necessary to incorporate this technology into experiments included constructing the tuned Q -damper circuit (resonating at the same frequency as the coil), inductively coupling it to the main coil with a series air core transformer, introducing resistance into the Q -damper circuit, such that one broad and shallow peak can be observed with a return loss meter through the probe's drive port, and turning the Q -damper on with a logic signal for a short period of time following transmission pulse to dissipate the energy stored in the main coil, while keeping it interrupted during transmis-

sion and signal acquisition. The Q -damper's operation has been demonstrated during a low frequency NQR experiment using the TONROF multi-pulse sequence, leading to the SNR improvement by a factor of 4.9.

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