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Detection and estimation of magnetization induced resonances in unilateral nuclear magnetic resonance (NMR) sensors

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In this work a systematic identification of factors contributing to signal ringing in unilateral nuclear magnetic resonance (NMR) sensors is conducted. Resonant peaks that originate due to multiple factors such as NMR, electrical, magneto-acoustic, core material response, eddy currents and other factors were observed. The peaks caused by the measurement system or electrical resonances and induced magnet vibrations are further analyzed. They appear in every measurement and are considered as interference to signals received from the magnetic core. Forming a distinction between different peaks is essential in identifying the primary contribution to the captured resonant signal. The measurements for the magnetic core indicate that the magnetization induced resonant peaks of the core have relatively higher amplitudes and shorter decay times at low frequencies. [http://dx.doi.org/10.1063/1.4974527]

I. INTRODUCTION

Unilateral nuclear magnetic resonance (NMR) techniques, based on open-ended magnets find wide applications in areas that are inaccessible using conventional magnet geometries.[1] Often magnetic cores are used within the unilateral NMR detection sensors due to the design of the magnet geometries.[2] These magnetic cores are used for flux concentration, higher magnetic field penetration and improved signal acquisition.[3] One of the major limitations of using magnetic cores is the measurement dead time caused by magnetization induced ringing of the magnetic core.[4,5] Several techniques such as modifications of magnetic core material properties, variations in measurement methods[4,6] etc. have been implemented to counteract this limitation. However, besides this limitation, it is apparent that signals can be misinterpreted if the origin of the signal is not identified. Thus, to obtain a better understanding of the measurement it is necessary to distinguish between signals originating from the magnetic core and signals arising due to variations in external magnetic field strength,[1] induced eddy currents in sample/magnet[7] and magnetization induced vibrations[8,9] in the magnetic core.

Pulsed resonance method, commonly employed by unilateral NMR measurement systems, consists of repeated application of an excitation pulse and detection of induced signals in a pick-up coil. It is a known method for studying magnetization induced resonant peaks.[10] In this work, a pulsed resonance method is used for systematic analysis and identification of factors contributing to signal ringing in unilateral NMR sensors. The findings of this study reveal resonances from three predominant sources namely: electrical, vibrational and material. Overall, these findings would be highly beneficial in estimating the origin of resonances, improvements in system sensitivity and rapid data acquisition.

II. THEORY

Prior works[9,10] describe that variations in magnetization can lead to occurence of mechanical vibrations in structures. These vibrations, often termed magneto-acoustic noise are dependent on the

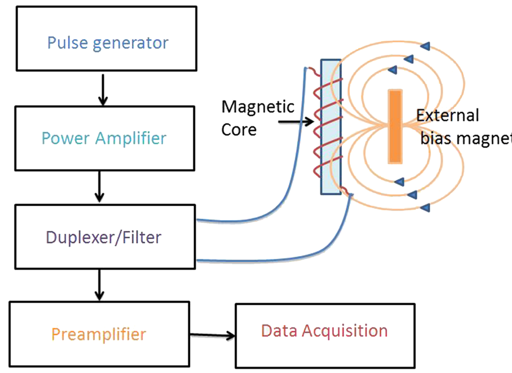


FIG. 1. Schematic representation of measurement system. The pulsed sinusoidal is generated by the pulse generator, amplified by the power amplifier, filtered and applied to the inductive load. Signals are received at the duplexer after a 100 μs delay, amplified and processed at the data acquisition unit. The shielding box encloses the magnetic core and the external bias magnet.

magnetizing frequency[9] and the geometry of the sample. In our experiment as displayed in Fig.1, a pulsed sinusoidal is applied to an inductive load that surrounds a magnetic core. A permanent magnet is placed adjacent to the coil to provide an external biasing field. It is expected that the magnetic core will experience vibrations in free space and at the same time the magnet will also be influenced by the field excitation signal. Mathematically, the resonant modes will occur when the length of the sample is a quarter wavelength for a constrained sample and a half wavelength for an unconstrained sample. Higher modes can be observed at integral multiples of quarter or half wavelengths respectively.[9] Thus, the n_{th} harmonic of resonant frequency for an unconstrained sample or the magnetic core in this experiment, f_s, is defined as[9]

$$f_s = \frac{n}{2l}\sqrt{\frac{E}{\rho}} \tag{1}$$

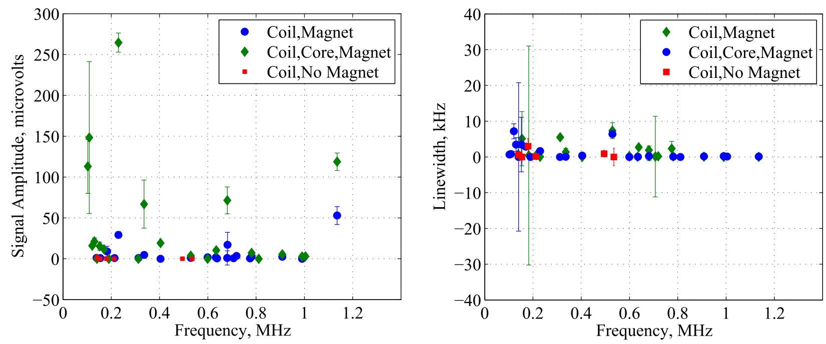
Similarly, the nth harmonic of resonant frequency for the constrained magnet, f_m, can be defined as

$$f_m = \frac{n}{4l}\sqrt{\frac{E}{\rho}} \tag{2}$$

Here l is the length of the sample, E is the Young's modulus and ρ is the density of the material. Equations (1) and (2) provide an estimation of the vibrational modes due to the magnetic core and the magnet respectively. Since these resonant modes relate to the sample geometry and the magnetizing frequency they may require longer time to decay and therefore they are detrimental in on-site operations of unilateral sensors.

III. EXPERIMENTAL APPROACH

To determine resonant frequencies from different contributing sources a pulsed resonance experiment was conducted. Fig.1 is a systems level schematic of the measurement setup. An electromagnetic excitation is applied to an inductive coil and the measured signal is evaluated. A spectrometer is used to generate a pulsed sinusoid at a maximum power of 1 mW (−10 dBm). A power amplifier is then used to amplify the input signal to a maximum level of 4000 W (66 dBm). A coil, inductance of 4.95 μH, 30 turns, 25 mm diameter and 100 mm length is placed next to a NdFeB N42 magnet that provides an external bias field. The magnetic core is placed within the coil. The entire assembly (the coil, magnet and magnetic core) is placed within a shielded aluminium box to minimize interference from external sources.



(a)Peak Signal Amplitudes recorded at the inductive load

(b)Linewidths at each resonant peak recorded at the inductive load

FIG. 2. Representation of signal amplitudes and linewidths for inductive coil and biasing magnet respectively. The signal amplitudes and linewidths were estimated from the Fourier spectrum at each resonance. Errorbars are generated by averaging over 3 different repetitions.

IV. PRELIMINARY OBSERVATIONS

In order to determine the origin of multiple resonant peaks, pulsed resonance measurements were conducted over a frequency range of 0.1 to 1.4 MHz and resonant frequencies were identified by application of narrowband (20 μs) and broadband (200μs) pulses at each particular resonant peak. The resonances are quantified on the basis of two parameters, namely the peak signal amplitude and linewidth at each resonance. A powdered iron sample was used as the magnetic core for this experiment. Fig.2(a), 2(b) clearly highlight the overlap between signals from the coil, magnet, magnetic core and external noise. These may all be assumed to be resonances due to the magnetic core and since Fig.2(a), 2(b) show that there is an overlap of signals due to variations in the core's magnetization it is necessary to determine the contributing factor for each resonance.

V. RESULTS AND DISCUSSION

Based on the observations in Fig.2(a), 2(b), the contributions to the observed signal from possible different sources i.e. electrical, vibrational and the magnetic core need to be distinguished.

A. Contributions from the measurement system

To determine the contributions due to measurement system, input signal and loading effects, pulsed resonance measurements were conducted with a matched 50Ω load and an inductive load of inductance 4.95μH, over the entire measurement frequency range. The pulse duration and repetition rate were set to 200μs and 500ms respectively. Since these correspond to low frequencies (lesser than 0.1MHz), it is understood that they do not appear as resonant peaks in the measurement. The self resonance of the coil was also measured using a network analyzer and was found to be at frequencies (greater than 25 MHz) beyond the frequency range of interest. This implies that self resonance of the coil cannot be observed in Fig.2(a). As in Fig.3(a), 3(b), certain resonant frequencies with low signal amplitudes are identified when a matched resistive load is connected to the system. Fig.3(a), 3(b) show that some of these resonant peaks also repeat when the inductive load is connected to the system. This implies that these resonances are occuring due to the measurement system itself. From Fig.3(a), 3(b), while the signal amplitudes are comparable at the overlapping resonant peaks, the linewidth of one of the resonant peaks (530 kHz) decreased with inductive loading as observed in Fig.3(b). This implies that signals originating from the system will take a longer time to decay at a frequency of 530 kHz. It is important to note that other resonant peaks have low amplitudes and linewidths (Fig.3(a)) and can be considered in further measurements as noise.

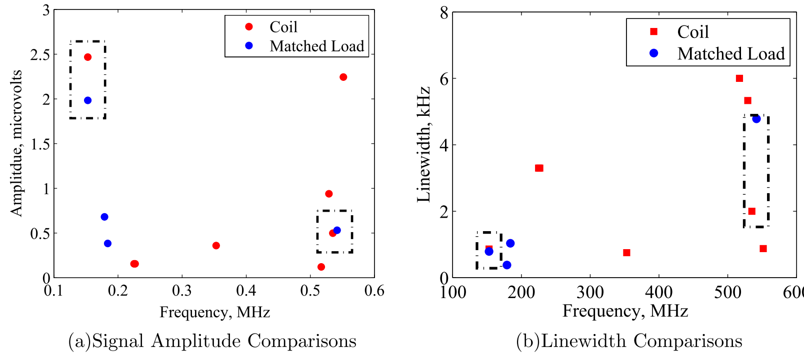


FIG. 3. Comparisons of ringing parameters for a matched resistive load and an inductive load (coil). The signal amplitudes and linewidths are estimated from the Fourier spectrum of the measured signal.

B. Contributions from the external bias magnet

A NdFeB N42 magnet was used to create a single-sided external biasing field. All the pulsed field measurements were repeated in the presence of this magnet. New resonant peaks, besides the resonant frequencies of the system as observed in Fig.2(a) are observed in Fig.4(a). These resonant peaks are considered to originate due to surface currents induced in the magnet and changes in the effective magnetic field around the coil. The surface(eddy) currents are also considered to be a source of mechanical vibrations for the magnet. Then the modes induced in the magnet can be calculated using equation (1). Due to the nature of our experiment, the vibrations due to the magnet are also recorded by the pick-up coil. Measurement results show that multiple modes and harmonics are induced in the magnet itself. A comparison of the calculated and measured harmonic modes for the magnet may be found in Table I. It was observed that only higher order modes can be observed since the frequency of operation is from 0.1 to 1.4 MHz. The peaks caused due to the magnet's vibrations are also present when the magnetic core is placed within the coil. From Fig.4(a) as expected, it is

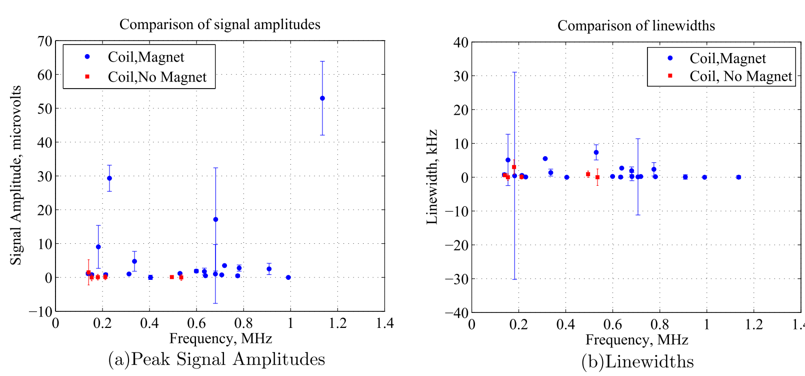


FIG. 4. Comparison of signal amplitudes and linewidths due to both the coil and magnet. Error bars were generated by averaging over 3 different measurements.

TABLE I. Vibrational modes induced in the magnetic core and magnet.

Material	E *GPa*	ρ kg/m^3	l m	$f_{calculated}$ kHz	Harmonic number n
Core	140	7000	0.094	24	6,7,8,13,14,17
Magnet	160	7500	0.1016	11	9,10,15,17,20

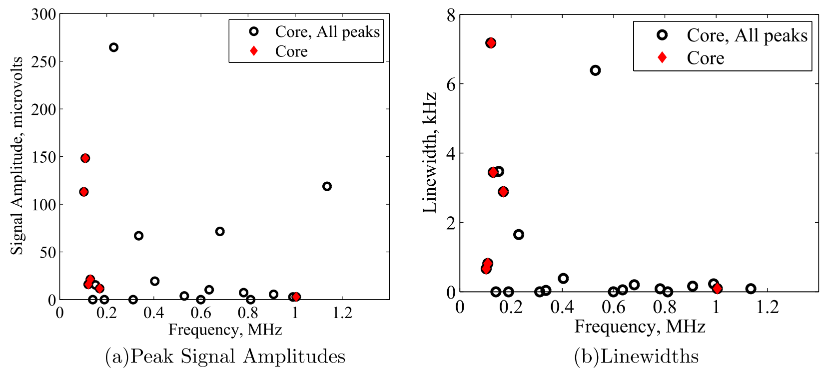


FIG. 5. Comparison of signal parameters due to coil, magnet and magnetic core. The peaks which are considered to originate due to the measurement assembly and due to the magnet are eliminated in the core measurements in these graphs.

observed that the resonant peak signal amplitudes increase in the presence of the magnet. Meanwhile the linewidths depict minimal variations in presence/absence of the magnet as in Fig.4(b).

C. Magneto-mechanical and core material contributions

Besides vibration modes in the magnet, mechanical vibrations are also induced in the magnetic core material as observed in Table I. In our experiment, there were peaks at specific resonant frequencies that could not be accounted for by either mechanical or system contributions. These peaks are considered to arise due to magneto-mechanical effects induced in the magnetic core. Fig.5(a) and 5(b) depict these resonant peaks after eliminating peaks caused due to the magnet and the system. In our experiment, these peaks are considered to originate due to intrinsic material properties of the magnetic cores. In some cases, due to the inhomogeneous nature of the magnetic field, some of the peaks may also appear to have shifted from expected frequencies. At the same time, addition of the magnetic core to the inductive coil changes the inductance to 18.67 μH. It is expected that the electrical resonant frequency for the inductive load would shift to a lower frequency with an increase in inductance.

Based on the pulsed resonance measurements, it can be confirmed that different resonant peaks originate from different sources. While the peaks from the measurement system and the magnet may be easily decoupled, identifying peaks due to the magnetic core requires further analysis. In particular, if some peaks due to the magnetic core overlap with the peaks due to the system/magnet they are not easily identifiable. At the same time, due to the inhomgeneous nature of the external magnetic field, all the vibrational modes may not be energized equally.

VI. CONCLUSIONS

In this work an approach to determining the origin of pulse induced resonant peaks has been presented. Based on the results, the peaks introduced due to the mechanical oscillations in the magnet, due to the measurement system and due to the magnetic core can be distinguished. It is understood that with variations in the magnet, magnetic field strength and magnetic core, the resonant peaks will shift in frequency but will still be present and will respond in the same way. It is also necessary to highlight that multiple resonant peaks were not originating only due to the magnetic core. Thus, creating a distinction is vital to determine the signals which are directly received from the magnetic core material.

VII. FUTURE WORK

On the basis of this work, a method to identify peaks from multiple contributing sources is established. While these peaks also depend on the measurement parameters, the contributions due to the magnetic core need further investigation and analysis. Especially the effect of external field inhomgeneity on the frequency, signal amplitude and linewidth needs to be analyzed. Ability to distinguish between different resonant peaks will be a vital resource for unilateral NMR sensors users such as oil well-logging engineers.

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