LANDMINE DETECTION BY NUCLEAR QUADRUPOLE RESONANCE (NQR)

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ABSTRACT

Landmines continue to threaten U.S. and allied forces. Conventional mine detection sensors, such as ground penetrating radar (GPR), can give many false alarms due to natural and manmade objects in the ground having mine-like characteristics to these sensors. This can result in a slow advance rate as the forces must deal with these false alarms. Nuclear quadrupole resonance (NQR) technology is being developed by the U.S. Army for application to landmine detection as a confirmation sensor to verify the presence of landmines and eliminate false alarms from GPR. NQR technology has the capability to detect and discriminate explosives from other items in the environment and it can discriminate among the different types of explosives found in landmines.

Recent field testing of an early prototype NQR landmine detection system developed by Quantum Magnetics, Inc. (QM) demonstrated high probability of detection and probability of false alarm rejection at scan times of about 20 seconds for TNT and a few seconds for RDX at 20°C. Current NQR research and development by the Army is focused on reducing the scan time for TNT. In 2004, the U.S. Army RDECOM CERDEC Night Vision and Electronic Sensors Directorate (NVESD) established a laboratory to investigate advanced NQR techniques for detection of landmines at Fort Belvoir, Virginia. The laboratory was established in collaboration with the U.S. Naval Research Laboratory (NRL), QM, King's College, London and the UK Defence Science and Technology Laboratory (Dstl). This paper reviews the basics of NQR technology, describes the capabilities of the laboratory at NVESD, and discusses the use of explosive simulants and proposed methods of reducing the scan time.

1. INTRODUCTION

Nuclear quadrupole resonance (NQR) methods of mine detection rely on the observation of radio-frequency (RF) signals from the ^{14}N nuclei present in the explosive (Hirshfeld and Klainer, 1980; Grechishkin, 1992; Rowe and Smith, 1996; Garroway et al., 2001; Deas et al., 2002). TNT and RDX are the most common explosive fills of landmines and are suitable for NQR detection because they each consist of solid crystals and contain quantities of nitrogen (see fig. 1).

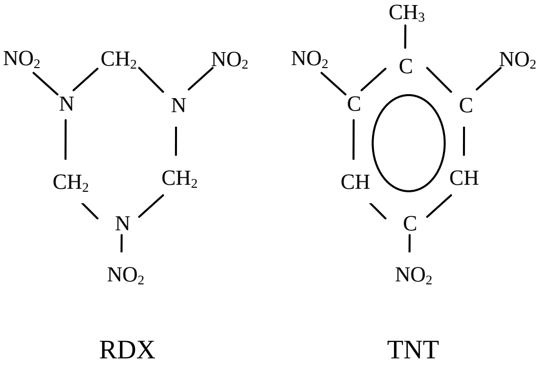

Fig. 1; Chemical structures of RDX and TNT

The frequencies of these signals lie between 0.5 and 6 MHz; they are characteristic of a given explosive and provide a positive identification. From the intensity of the signal it is also possible to estimate quantity or depth. Remote RF antennas can be designed which can detect signals from suitable materials at distances of approximately 20 cm (Barrall et al., 2004). Furthermore, signals are only seen in solids or solid-like materials, and because of the highly compound-specific nature of NQR frequencies, there is little, if any, false alarms from other nitrogen-containing materials which may be present in the mine casing or the surrounding terrain.

The RF spectroscopic technique of NQR is one in which the applied radiation drives transitions between the quadrupole energy levels of an atomic nucleus (Smith, 1986). These levels arise because of the interaction between the electric quadrupole moment of the atomic nucleus and the electric field gradient at the nucleus due to surrounding charges. The important quadrupolar nucleus in explosives is ^{14}N, a spin 1 nucleus, the energy level diagram and allowed transitions for which are shown in figure 2. There are three allowed transitions in the general case, one frequency (ν_x or ν_+) being the sum of the other two (ν_y or ν_-, ν_z or ν_0). These frequencies are

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14. ABSTRACT

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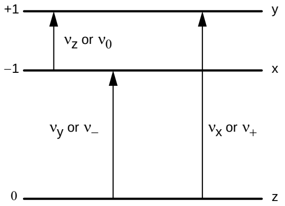
related to quantities known as the quadrupole coupling constant and asymmetry parameter by the equations shown in figure 2, where (e^2qQ/h) is the quadrupole coupling constant, e is the charge on the electron, h Planck’s constant, $q = q_{zz}$ the maximum principal component of the electric field gradient and Q the nuclear electric quadrupole moment. η is the asymmetry parameter defined as the difference between the other two principal components (q_{xx} and q_{yy}) of the electric field gradient tensor divided by q; it is a positive number lying between zero and one.



$$\nu_x = \tfrac{3}{4}\frac{\left(e^2qQ\right)}{h}\left(1+\tfrac{\eta}{3}\right)$$

$$\nu_y = \tfrac{3}{4}\frac{\left(e^2qQ\right)}{h}\left(1-\tfrac{\eta}{3}\right)$$

$$\nu_z = \tfrac{1}{2}\frac{\left(e^2qQ\right)}{h}\eta$$

Fig. 2; ^{14}N Quadrupole levels and allowed transitions.

The detection of TNT by NQR is further complicated by the fact that it is known to exist in at least four crystallographic forms two of which are monoclinic and two orthorhombic (Gallagher et al., 1993; Golovina et al., 1994; Gallagher and Sherwood, 1997). One monoclinic form is known to be often heavily twinned. NQR can detect the differences in resonant frequencies caused by these different crystalline structures (Marino and Connors, 1983; Deas et al., 2004). In addition, the temperature of a NQR sample has an effect on its molecular kinetics, thereby changing the NQR time constants and electric field gradient. Therefore the NQR frequencies of the resonant lines of explosives change with temperature.

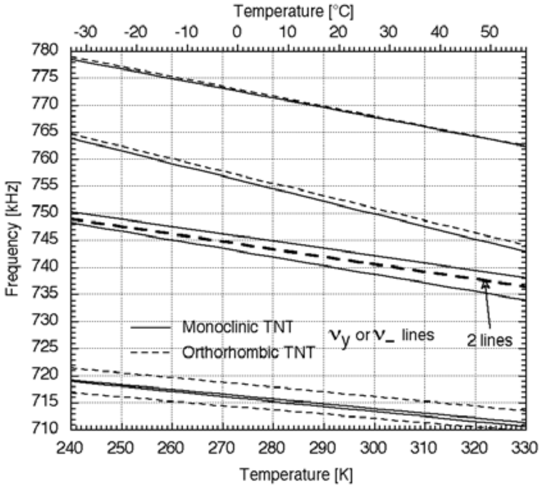


Fig. 3; Frequency vs. temperature data for the ν_y lines of TNT

The temperature dependences of the ν_x and ν_y resonant lines of both crystalline forms of TNT are shown in figures 3 and 4.

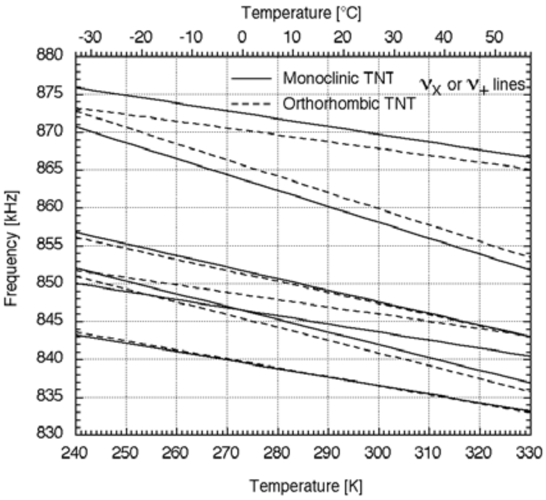


Fig. 4; Frequency vs. temperature data for the ν_x lines of TNT

2. THEORY

The detectable NQR signal is produced when the nuclei absorb the resonant RF radiation. This absorption has the affect of rotating the nuclei about the direction of the exciting RF radiation. The RF radiation emitted by the excited nuclei whilst in their non-equilibrium state can then be detected and the maximum magnetization per unit volume produced by the excited nuclei is given by,

$$M_u = \frac{h^2 \nu_Q N_0 \gamma}{12\pi kT} \qquad [1]$$

Where h =Planck’s constant
ν_Q=quadrupolar resonant frequency
N_0=number density of resonant nuclei
γ =gyromagnetic ratio of the ^{14}N nucleus
k =Boltzmann’s constant
T =sample temperature

The detectable magnetization from pulsed NQR detection begins to decay exponentially immediately after it is excited by an excitation pulse and this is known as the free induction decay (FID). A FID can be regenerated to form an echo and echoes have maximum intensity between RF pulses in a multiple pulse train. When dealing with extremely weak NQR signals from explosive samples many responses need to be accumulated to achieve an acceptable signal-to-noise ratio (SNR). For this purpose, it is customary to use extended trains of pulses accumulating the observed responses between pulses to enhance the SNR. One example, giving echo signals, is known as pulsed spin locking (PSL) or spin lock spin echo (SLSE) which can be represented by,

$$\alpha_{0^0} - (\tau - \alpha_{90^0} - \tau -)_n \qquad [2]$$

where α represents the pulse width selected to optimize the signal, the subscripts denote the RF phase, τ determines the pulse spacing, which is 2τ after the first two pulses, and n determines the number of pulses in the train with the optimum value depending on the relaxation times of the explosive. The entire pulse sequence is usually repeated many times for further signal averaging.

The table below gives the time constants that become important when using such pulse sequences and signal averaging.

NQR TIME CONSTANTS

T_2^*	Effective spin-spin relaxation time	Governs decay rate of signal and linewidth of resonances (dependant on temperature)
T_{2e}	Echo relaxation time	Governs decay rate of echoes and is dependant on τ and temperature
T_1	Spin-lattice relaxation time	Governs return of sample to equilibrium and hence how quickly signal averaging can occur (dependant on temperature)

The magnetization from a NQR sample given in equation 1 can be combined with antenna specific variables to give a theoretical estimate of SNR of a received NQR signal after a single acquisition. This was first estimated for nuclear magnetic resonance (Bloembergen et al., 1948) and this estimate can be modified for pulsed NQR and converted into SI units to give,

$$SNR = M_u \mu \mu_0 \frac{NA\omega_Q \xi}{\sqrt{kTBr}} \qquad [3]$$

Where μ_0=permeability of free space
N =number of turns of antenna coils
A =area of antenna coils
ω_Q=resonant frequency (radial)
ξ =coil filling factor
T = temperature
B =receiver bandwidth
r =resistance

3. EXPERIMENTAL

The laboratory at U.S. Army Night Vision and Electronic Sensors Directorate (NVESD), Fort Belvoir, Virginia employs a Tecmag spectrometer to generate RF excitation pulses and digitize NQR signals from samples. A typical block diagram of the experimental set-up is shown in figure 5 and the actual apparatus is shown in figure 6. RF excitation pulses generated by the Tecmag spectrometer are amplified by a power amplifier and are applied to a tuned antenna that is either a solenoid for analytical experiments or single sided for practical landmine detection experiments. Either the same antenna or a secondary one receives the NQR signal generated from the RF excitation pulse and this is amplified by a low noise amplifier before being digitized by the spectrometer. The digital data can then be processed and displayed in the time or frequency domain.

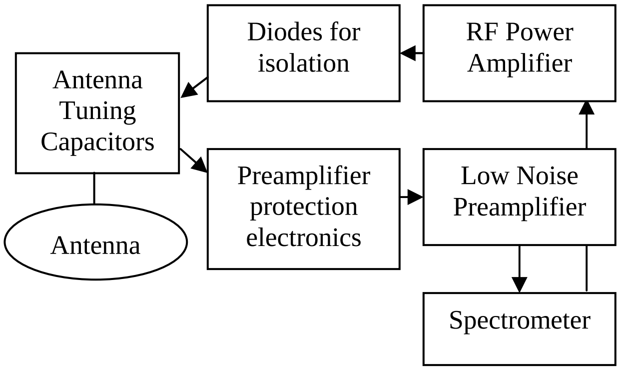


Fig. 5; Block diagram of typical NQR detection system

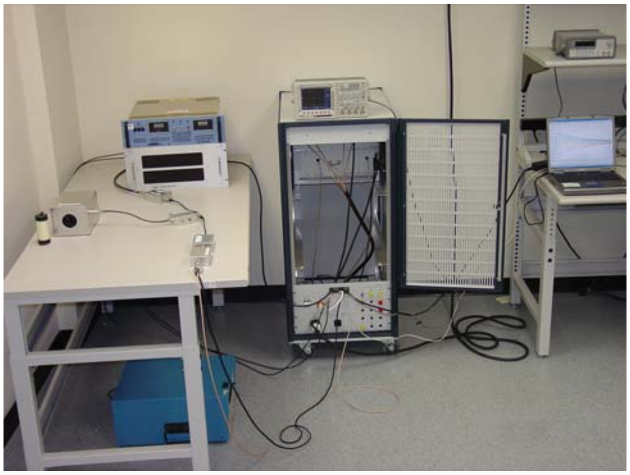


Fig. 6; NQR laboratory apparatus for explosive detection

In addition to the basic experimental set-up, a circuit to damp the antenna quality factor has been installed by QM. This circuit enables signal enhancement through the ability to apply excitation pulses at a more rapid rate and therefore accumulate more echo data in a given time.

4. RESULTS

Simulants for TNT and RDX explosives are normally used in NQR laboratories due to safety concerns and logistical difficulties in transporting explosives. However, as NQR is extremely sensitive to changes in chemical structure and crystalline lattice, representative simulants are difficult to obtain. Desensitized forms of RDX and TNT have been obtained from XM-Division, Van Aken International and are known as nonhazardous explosives for security training and testing, (NESTT). These NESTT simulants have actual explosive content which is distributed in a nonhazardous medium and is classified by the Department of Transportation (DOT) classified as not an explosive. However, the explosive content still returns an accurate representation of its NQR properties and the main difference is that the NESTT materials have significantly reduced density of resonant nuclei (Hudson et al., 2004). A NQR frequency spectrum acquired in the NQR laboratory is shown in figure 7 and it can be seen from this that the NESTT sample comprises mostly of the orthorhombic crystalline phase of TNT. An adequate SNR for landmine detection can be seen in under 10 seconds in a solenoid probe with anti-personnel quantities of the TNT NESTT stimulant.

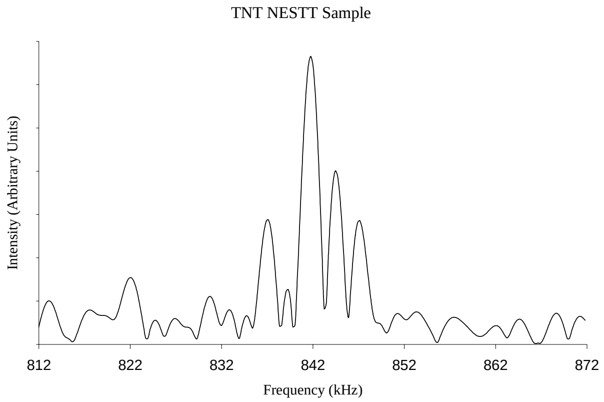


Fig. 7; NQR frequency spectrum of four ν_x lines of TNT NESTT simulant

Calculations and models based on the theory given in equations 1-3 are being developed to compare experimental and theoretical SNRs obtainable from NQR detection of explosives.

5. CONCLUSIONS

A NQR laboratory has been developed at U.S. Army NVESD, Fort Belvoir, Virginia that is specifically designed for the detection of explosives found in landmines. Explosive simulants are being examined in the laboratory and SNRs are being obtained in short scan times in controlled, shielded conditions. Theoretical calculations and modeling are under development to better predict NQR explosive detection performance and single-sided antennas are being designed to further reduce scan times required for NQR to detect explosives in landmines.

It has been shown that NQR can perform the requirements of a landmine confirmatory sensor in shielded conditions in the laboratory. However, random and discrete interference is still a significant engineering challenge when an NQR system is used in practical unshielded conditions.

6. FUTURE WORK

One major concern in development of a NQR sensor is its sensitivity to the NQR response of a given mass of explosive. The objective is to have the capability to detect small quantities of explosives at maximum distances from the antenna. The sensitivity of an NQR sensor is dependent on the pulse sequence parameters (pulse peak amplitude, width and spacing, and number of pulses), the transmitted carrier frequency, the characteristics of the receive antenna (thermal noise, gain and ratio of antenna diameter to explosive diameter, similar to a solenoid “filling factor”) and receiver electronics (thermal noise in preamplifiers). Since the NQR signal voltage induced on the sensor decreases rapidly with increasing axial distance between the receive antenna and the explosive, the antenna should be designed to be as close as practical to the explosive. For a confirmation sensor, the antenna can be placed to rest on the ground directly over the mine. However, a priori knowledge of the burial depth (i.e., soil overburden) and location of a buried mine will be imprecise. The uncertainty in depth is dependent on the tactics used by those employing the mines. The location uncertainty is due to limitations of the primary sensor suite, which results in both cross-track and down-track errors. The sensor must be designed (e.g., selection of antenna diameter) to accommodate these uncertainties. Also, the average temperature of the main charge explosive in the mine must be estimated and input to the sensor for determining the optimal carrier frequency and pulse sequence parameters for transmission. An accuracy of about ± 5ºC is needed. The average temperature is used since the explosive will have a temperature gradient across it due to the difference between the surface temperature and the temperatures at various depths in the ground caused by solar heating. Accurate techniques for automatically estimating the average explosive temperature prior to each scan are still needed. The solution will likely involve a combination of a remote temperature sensor, such as an infrared device, and a model that takes the sensor output (e.g., measured ground surface temperature) and calculates the likely range of temperatures.

Experiments are being designed at the U.S. Army NVESD NQR laboratory to compare two fundamentally different NQR antenna designs; antennas comprising of low and high inductance. A comparison of sensitivity to received NQR signal as well as susceptibility to electric fields and practical design issues will be performed between a typical low inductance and high inductance antenna.

Another concern in development of a NQR sensor is its ability to discriminate RF noise and interference from the NQR signal. Experiments are being designed to improve the isolation of NQR single sided antennas from RF noise and interference whilst maintaining maximum NQR signal sensitivity. Investigations as to how best to mitigate RF noise and interference using a passive NQR antenna and an extra receive channel digitizer will also be undertaken.

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