The Nuclear Magnetic Resonance Gyroscope: a Review

K. F. Woodman, P. W. Franks and M. D. Richards

(Admiralty Research Establishment, Slough)

A review of the nuclear magnetic resonance gyroscope (NMRG) as a rotation-rate sensor is presented. Most of the activity in the recent past on NMRG research originated in the USA and concentrated almost exclusively on forms of the NMRG utilizing optical-pumping techniques. To date, only the National Air Defence Centre at Warminster, Pennsylvania continues to pursue a low-cost variant of the NMRG while in the UK, only ARE (Slough) and Sussex University remain active in NMRG research. The emphasis on activity in the Navigation Division at ARE (Slough) has continued to be on cryogenic helium-3 ($^{3}$He) techniques and the use of superconducting shielding (although optical-pumping will also be pursued). The continuing incentive for NMRG research remains the requirement for a ship's low-cost inertial navigation system (SLINS).

1. INTRODUCTION. Research and development on the nuclear magnetic resonance gyroscope (NMRG) over the last decade has been aimed at providing an accurate low-cost alternative, in certain applications, to relatively expensive spinning-wheel gyros. A particular naval example currently employed in the Royal Navy is the ship's inertial navigation system (SINS) where the degree of engineering precision and special techniques (e.g. gas-bearings, etc.) to meet the requirement for a successful stand-alone inertial navigation system largely contributed to its very high cost. SINS MK II, for example, meets the very precise and accurate navigational and operational requirements but is very expensive to procure, is large and is costly to install, as well as support in service. Furthermore, the older technology means a physically bulky system, and as a result SINS often cannot be fitted in a variety of naval platforms where accurate inertial navigation and position-fixing is required.

Recognizing the problem for the future, the Royal Navy has decided to address the feasibility of providing a ship's low-cost inertial navigation system (SLINS) to replace the existing SINS variants, and more generally, to replace gyrocompasses in all other ships not otherwise carrying SINS. An extremely important but stringent characteristic of any SLINS contender is that it must be comparable in performance to the existing SINS. Also, the alternative system must be simpler, smaller, lighter, easier to install and inexpensive to support. Furthermore, the initial cost of SLINS must be significantly lower than that of SINS, to the extent that the cost of SLINS must be comparable with the cost of existing compass stabilizer systems. The dry-tuned gyro (DTG) was once considered as an early contender as there was evidence that such a spinning-wheel gyro might provide a gimballed low-cost option. This approach has now been abandoned for a variety of reasons, not least of which is that it retains many of the disadvantages associated with gimballed spinning-wheel systems.
Instead, the possibility of a more radical approach became evident almost two decades ago but, mainly for technological reasons, it did not reach the necessary level of sophistication until quite recently. The ring-laser gyro (RLG), utilizing the Sagnac effect, has now become the leading contender for the rotation-rate sensor in SLINS. The RLG has the great advantage that there are no moving parts (apart from the mode-unlocking dither mechanism, which introduces problems of its own). Furthermore, the RLG can be used in a strap-down mode, thus doing away with the need for gimbals and, as a result, possesses a high dynamic range. However, a number of important technical problems remain to be solved before the RLG is likely to possess a performance comparable to the existing SINS. Because of the complex fabrication techniques and the high degree of engineering precision needed to meet the naval specification, it remains to be seen how low-cost a device the fully engineered RLG and its electronics package really is.

The other low-cost contender, the subject of this paper and possessing similar advantages to those enjoyed by the RLG, is the nuclear magnetic resonance gyro (NMRG). Particular variants of this rotation-rate sensor have been successfully constructed and tested by a number of organizations in the USA. Detection of rotation rates corresponding to Earth’s rotation rate and, in some cases, rather lower, have been reported and although a number of devices offering low- to medium-quality performance appear to have been constructed and patented, none had a performance comparable to that of SINS.

Nevertheless, the NMRG is much simpler in construction than the RLG and does not require the precise fabrication techniques absolutely necessary for a successful RLG, and so the NMRG retains its potential as a truly low-cost device. It does, however, have technical problems peculiar to itself which must be overcome if the NMRG is to remain as a serious contender for SLINS and an alternative to the RLG. The NMRG has never enjoyed a level of funding and support in the UK comparable to that in the US, nor a level of support comparable to that given to RLG work in the UK. As a result, the technical realization of the NMRG lags behind that of the RLG. The NMRG is, therefore, not a serious contender for the first version of SLINS but could well provide considerable advantages, including further cost savings, in a possible later version for the late 1990s. While the impetus for the present activity remains military needs, if the eventual cost is comparable to today’s gyro-compasses, the NMRG could well find commercial applications.

Only ARE (Slough) in the UK continues to support the NMRG research and development programme, both by in-house effort\(^1,2\) over a number of years and, more recently, by sponsoring extramural research at Sussex University.\(^3,4\) Over the coming year, it is anticipated that some useful results will be achieved and thus point the way forward for a successful NMRG.

2. NMRG PRINCIPLES. Nuclear magnetic resonance. The physical principles underlying the phenomenon of NMR are well understood and suitable descriptions abound in the literature.\(^5,6\) Nuclear magnetic resonance is a weak phenomenon, and consequently can be difficult to observe. It was not conclusively demonstrated that NMR occurred in bulk materials until the 1940s,\(^7,8\) although the principles underlying the precession of charged atomic particles in an applied magnetic field
had been predicted much earlier from Larmor’s theorem (Sir Joseph Larmor, 1857–1942). In the phenomenon of NMR it is the atomic nucleus which is affected by an externally applied magnetic field, as shown schematically in Fig. 1. Certain atomic nuclei which have a spin also possess a magnetic moment ($\mu_z$) and can be made to precess about a direction parallel to the direction of an externally applied magnetic field ($B_0$) with a characteristic frequency ($\omega_L$) known as the Larmor frequency given by the expression:

$$\omega_L = \left( g_N \frac{e}{2M_N} \right) B_0$$  \hspace{2cm} (1)

where $g_N$ is the nuclear $g$-factor, $M_N$ the mass of the nucleus and $e$ its electronic charge. The term inside the brackets of equation (1) is usually combined into a single constant, the gyromagnetic ratio, $\gamma$ (sometimes also referred to as the magnetogyric ratio, since $\gamma$ is the ratio of the magnetic moment ($m$) to the resultant angular momentum ($G$) resolved along the direction of $B_0$).

Not all nuclei exhibit the phenomenon of NMR. Table 1 lists some of the nuclear species employed in various forms of the NMRG. Furthermore, a single isolated precessing nucleus does not represent a feasible NMRG. Instead, any practical design uses a small sample of the nuclear species (usually in gaseous form).
containing a large number of atoms and their nuclei (for instance, 1 cm$^3$ of $^3$He gas at STP contains about $10^{24}$ nuclear spins). It is how this ensemble of atoms behaves that determines whether an NMRG is possible or not, and many practical problems need to be resolved before an NMRG is realized.

### Table 1. Examples of Nuclear Species Employed in the NMRG

<table>
<thead>
<tr>
<th>Nuclear species</th>
<th>$I$ (units of $\hbar$)</th>
<th>$\nu$/MHz</th>
<th>$\mu/\mu_N^*$</th>
<th>Natural abundance per cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1$H (proton)</td>
<td>$\frac{1}{2}$</td>
<td>+2.79285</td>
<td>42.5760</td>
<td>99.985</td>
</tr>
<tr>
<td>$^3$He</td>
<td>$\frac{1}{2}$</td>
<td>-2.12765</td>
<td>32.4338</td>
<td>0.00013</td>
</tr>
<tr>
<td>$^{129}$Xe</td>
<td>$\frac{1}{2}$</td>
<td>-0.7770</td>
<td>11.779</td>
<td>26.44</td>
</tr>
<tr>
<td>$^{199}$Hg</td>
<td>$\frac{1}{2}$</td>
<td>+0.5040</td>
<td>7.6120</td>
<td>16.84</td>
</tr>
<tr>
<td>$^{201}$Hg</td>
<td>$\frac{1}{2}$</td>
<td>-0.5880</td>
<td>2.8781</td>
<td>23.13</td>
</tr>
<tr>
<td>$^{87}$Rb</td>
<td>$\frac{1}{2}$</td>
<td>+2.750</td>
<td>13.932</td>
<td>27.85</td>
</tr>
</tbody>
</table>

* $\mu_N$ is the nuclear magneton and has the value $5.050824 \times 10^{-27}$ JT$^{-1}$.

**Rotation.** If such a system of nuclear spins is made to rotate at angular rate, $\Omega_R$ (the rotating coordinate frame) with respect to a stationary observer (the laboratory frame), the measured precessional rate also changes. The ability to alter the observed precessional frequency by rotation is usually expressed in the simple form:

$$\omega_0 = -(\gamma B_0 \pm \Omega_R)$$

where $\omega_0$ is the observed or measured precessional rate in a magnetic field, $B_0$, and where $\omega_L = \gamma B_0$ as before in equation (1). The expression governing $\omega_0$ also highlights a most important consequence for the NMRG. It is not possible to distinguish between changes in $\omega_0$ caused by changes or fluctuations in $B_0$ from changes solely due to rotation. It will be absolutely necessary in any practical version of the NMRG to maintain the magnitude of $B_0$ constant to a very high degree or, alternatively, to employ techniques which effectively compensate for any variations in the value of $\omega_0$ caused by $B_0$ fluctuations. Two compensation techniques have been successfully employed in practical variants of the NMRG.

With two nuclear species (a and b) in the same cell, two 'Larmor' frequencies are available for measurement ($\omega_a$ and $\omega_b$) so that the rotation rate experienced by the sample cell ($\Omega_R$) can be determined without knowledge of the polarizing flux, $B_0$, where $\Omega_R$ is given by the expression:

$$\Omega_R = \frac{(\gamma_b/\gamma_a) \omega_a - \omega_b}{(1 - \gamma_b/\gamma_a)}$$

The only other parameter which needs to be determined is the ratio $\gamma_b/\gamma_a$, which must be measured to the same accuracy as the frequencies.

The second technique utilizes a pair of cells, each of which contains a mixture of the two nuclear spins as before but each being in an oppositely oriented field.

There are now four frequencies available for measurement, and $\Omega_R$ can be determined without a knowledge of $B_0$ and $\gamma_b/\gamma_a$ i.e.:

$$\Omega_R = -\frac{1}{4} \left[ \omega_a + \omega_b + \omega_a^* + \omega_b^* \right]$$

(4)
where the * refers to the spin system in the oppositely directed magnetic field. Despite the apparent simplicity of equation (4), there is a hidden requirement that the two steady magnetic fluxes, $B_0$ and $B^*_0$, must be maintained equal and opposite to each other with a degree of accuracy comparable to the accuracy with which the frequencies are measured (e.g. 1 part in $10^8$ or better for Earth's rotation rate). So far these two compensation techniques have been applied to optically pumped variants of the NMRG. In contrast, methods of maintaining the magnetic fields constant and homogeneous over the sample have relied on the use of superconducting shields. Present activities at ARE (Slough) suggest that a combination of optical pumping and superconducting shields may well represent the best combination.

3. SYSTEM CONSIDERATIONS. Rotation rate. Unlike the spinning-wheel gyro, the NMRG has no inherent moment of inertia and thus does not provide a physically maintainable reference direction in inertial space; it is a rate-integrating single-axis rotation sensor. While detection of Earth's rate is an initial very necessary step, the NMRG for marine use must be capable of detecting rotation rates at least two orders of magnitude lower. Table 2 summarises these broad requirements, and it will be necessary to develop techniques for the measurement of these extremely small frequencies ($\approx 10^{-8}$ Hz) and phase changes ($0.05$ µrad), usually by comparison with some highly stable reference sources.

<table>
<thead>
<tr>
<th>Motion</th>
<th>Degree/hour</th>
<th>Frequency (Hz)*</th>
<th>Phase Change (rads)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth's diurnal period (23 h 56 min 4.3 s)</td>
<td>15.04</td>
<td>$1.16 \times 10^{-5}$</td>
<td>72.90</td>
</tr>
<tr>
<td>Ship travelling at 20 kt over sea at equator</td>
<td>0.33</td>
<td>$2.58 \times 10^{-7}$</td>
<td>1.62</td>
</tr>
<tr>
<td>Acceptable drift rate</td>
<td>0.01</td>
<td>$7.71 \times 10^{-9}$</td>
<td>0.05</td>
</tr>
</tbody>
</table>

* 1 Hz = $360^\circ$/s.

Modern frequency standards possessing long-term stabilities in excess of 1 part in $10^{12}$ (e.g. caesium—1 part in $10^{12}$; rubidium—1 part in $10^{10}$) should just cope with NMRG needs (the hydrogen maser, despite having a very high long-term stability in the region of 1 part in $10^{16}$, is not considered a viable option at present due to its very high cost).

Sensitivity. Sensitivity is to a first approximation synonymous with $S/N$ ratio (there are other considerations, such as relaxation processes). When the external magnetic field is applied, the nuclear spins line up parallel and anti-parallel to the field direction, with a small excess in the direction parallel to the applied magnetic field. It is this excess number which produces a net magnetization ($M$) and which gives rise to the precession signal. The excess number of spins is exponentially dependent on both the absolute temperature ($T$) and $B_0$, i.e.:

$$\frac{N_e}{N_g} = \exp \left( -\frac{\gamma h B_0}{kT} \right)$$

(5)
(\(h\) is Planck constant and \(k\) is Boltzmann constant). Thus, either a high magnetic field or a low operating temperature is required. Unlike conventional room-temperature NMR spectroscopy, where values of \(B_0\) can exceed 10 T (10,000 G), a high magnetic field cannot be tolerated since it would give rise to a high Larmor frequency, which in turn would dictate a time standard of accuracy greater than can be presently achieved (NMR spectroscopy has Larmor frequencies in the tens of MHz and, for reasons which need not be further elaborated here, the Larmor frequency should not exceed a few tens of kHz where rotation-rate determination is required, as in the NMRG). Given the required range for \(B_0\) it is common practice in NMRG research to cool the gas sample to quite low temperatures, to liquid helium temperatures near 4.2 K, for example. This has the added bonus that cryogenic superconducting shielding can be employed, which in turn can be used to assist not only in achieving shielding from external magnetic influences, but also allowing regions of highly homogeneous magnetic fields within the superconducting shielding.

Even so the polarization (defined as the ratio \((N_e - N_g)/(N_e + N_g)\)) is often no greater than 0.01 per cent, giving usable if low \(S/N\) ratios. However, it is possible to greatly enhance the polarization by a technique known as optical pumping to values of the order of 70 per cent, with the consequently vastly improved \(S/N\) ratio.

Relaxation processes. NMR, in common with most oscillatory processes, suffers from the phenomenon of relaxation, that is, the signal from the precessing nuclei decays to zero with time. In an isolated nucleus precession, once started, would continue indefinitely and the macroscopic magnetization vector remain orientated at a constant angle to the direction of \(B_0\). In a bulk sample, interaction with the surroundings (through thermal motion effects, etc.) causes the magnetization vector to realign with the \(B_0\) direction, and in so doing gradually returns to its equilibrium value in a characteristic time, \(T_1\). Two macroscopic magnetizations are identified with the NMR process, a longitudinal magnetization \((M_z)\) parallel to the direction of \(B_0\) (z-axis) and a transverse magnetization \((M_{x,y})\) in the \(x-y\) plane and which arises when the sample has been polarized by a magnetic field \((B_1)\) perpendicular to \(B_0\) (there are other ways of initiating — and maintaining — precession). Both magnetizations are subject to relaxation (see Fig. 2), but it is the value of \(T_2\) which governs the practical realization of an NMRG. Ideally \(T_2\) should be hundreds of seconds long as it is only the transverse magnetization which is available for rotation measurements.

In one particular NMR technique, the d.c. method (see Fig. 2), a polarizing field, \(B_1\) (\(\gg B_0\)) is applied perpendicularly to \(B_0\) for a short time (short but > \(T_1\)). It is then removed, and the ensemble of spins are allowed to precess around the direction of \(B_0\), during which time a precession signal is available for measurement. It should be noted that, while the longitudinal magnetization returns to its equilibrium value with a time-constant \(T_1\), the transverse magnetization relaxes to zero with a time-constant \(T_2\). Achieving the necessary longer values for the relaxation times is seen as one major hurdle to a successful NMRG. The other requirement is the achievement of field homogeneity and stability. Magnetic field inhomogeneity shortens \(T_2\) and it has become customary to include a contribution
from field inhomogeneity in this relaxation time, denoting the combined effect by a new parameter, $T_2^*$. In order to resolve the Earth's rotation rate ($\approx 10^{-5}$ s$^{-1}$), it would be necessary to achieve a value of $250$ s for $T_2^*$ and an $S/N$ ratio of $500$ (27 dB). Rotation rates below Earth's rate require significantly longer relaxation times and a considerable improvement in the $S/N$ ratio.

Conventional proton magnetometers operate quite successfully in values of $B_0$ no higher than the Earth's magnetic field (of the order $4 \times 10^{-5}$ T) and changes in the indicated output can be observed at quite low rotation rates ($\approx 0.1$ Hz), thus easily demonstrating that the measured precession frequency varies with rotation rate. Figure 3 shows a typical low-resolution decaying sinusoid or free-induction-decay (FID) as the ensemble of spins precess about the $B_0$ direction (the value of $T_2$ in this instance was about 4 s).

Such magnetometers are low-order rotation-rate sensors, but their sensitivity is many orders of magnitude too low for use in any serious NMRG design. A low magnetic field and room-temperature operation yields a low polarizability, a crucial parameter in any NMRG concept. Although operation at 4.2 K with $^3$He
greatly improves the polarization, it is through the mechanism of optical pumping that suitable levels of polarization are achieved, and this in turn yields the necessary sensitivity for the detection of extremely low rotation rates (e.g. $10^{-6}$ Hz — as $\Delta f \approx (S/N)^{-\frac{1}{2}} \times (1/T_1^*)$). That the phenomenon of rotation-dependent frequency shift in the NMR signal is a real effect can be quite simply demonstrated. To achieve the high resolution needed in a useful NMRG requires far more ingenuity.

**Optical pumping.** Optical pumping is a technique widely employed in NMRG research to achieve relatively high levels of net nuclear magnetization (polarization) induced by irradiating the gas with circularly polarized light at a wavelength characteristic of the nuclear species. The precise interaction mechanism between the photons of the right-hand circularly polarized (RHCP) light, the electrons and the nuclei is complex. The net result remains that electronic angular momentum is transferred to the nuclei, producing a net nuclear magnetization. Figure 4 shows how the RHCP light (from an intense discharge lamp or a laser) is made to interact with the nuclear species for the two main optically pumped regimes. If the intensity of illumination is high enough and if the longitudinal relaxation time is of sufficient length, a considerable disparity in population levels can be attained, corresponding to polarization factors of the order of 40 per cent using lamps and up to 70 per cent in one reported example using lasers. The rules governing the optically pumped process for other nuclear species or combinations of species obey similar principles (e.g. for Xe, Hg, Rb, Kr). Details can be found in the literature and need not be reproduced here. Optical pumping gives long relaxation times, resulting in narrow linewidths and high S/N ratios.

**Fig. 4. NMRG optical pumping schemes using binary or duplicate cells**

(a) Single or binary species pumping scheme, using separated pumping and observation cells

(b) Binary species and duplicate-cell arrangement in oppositely oriented fields (optical read-out usually accompanies this technique)

| $\lambda = 10,830$ Å for $^4\text{He}$ |

**4. CANDIDATE SYSTEMS.** Optically pumped NMRGs. Optically pumped NMRGs currently represent the only successful variants so far developed by the US organizations Litton and Singer–Kearfott. An interesting consequence of optically pumped polarization enhancement is that it has encouraged these organizations to adopt wholly optical read-out methods to provide a measurement of the NMR
effect under rotation. Two optical techniques have been devised to sense rotation effects, both being sensitive optical magnetometers (see Fig. 5).

The first or Dehmelt technique, as favoured by Litton, involves the use of circularly polarized read-out light beams. The precessional motion of the nuclear magnetic moment causes a variation in absorption of the incident light traversing the cell. Therefore the light is intensity-modulated on passing through the cell due to the relative positions of the nuclear magnetic moments with respect to the incident light. This modulation is proportional to the rate of rotation of the cell.

The second technique (used by Singer—Kearfott) utilizes the principle of Faraday rotation. A linearly polarized read-out beam is passed through the sample cell and it is found that the plane of polarization oscillates back and forth at the Larmor frequency and with an amplitude proportional to the signal strength. This modulation in the plane of polarization of the read-out beam is transferred into amplitude modulation by means of a suitably orientated analyser and is thus a measure of the rate of rotation of the sample. The technique has the advantage that it is only sensitive to magnetic fields within a narrow band, and control of the magnetic field can be achieved independently. For a more detailed analysis of these optical read-out methods, the literature should be consulted.

The Litton NMRG consisted of a single sample cell containing $^{87}$Rb vapour, in addition to $^{85}$Kr and $^{129}$Xe as the nuclear species isotopes. The system also included a rubidium pumping lamp, optics, filter cell, magnetic field coils and mu-metal shielding cylinders. The read-out technique uses the Dehmelt principle. The intensity-modulated signal is received at the photodiode, where it is amplified and demodulated to remove the a.c. carrier frequency, resulting in the two Larmor sideband signals. The signals are then separated to provide the nuclear precessional phases, as well as the feedback signal for the ‘torquing’ of the magnetic moments and the control of the d.c. magnetic flux (i.e. $B_0$).

The optical system provides the correct spectral component of circularly polarized light for both optical pumping and the read-out process. This light traverses the cell at $45^\circ$ to $B_0$. Figure 6 shows a sectioned view of the gyro, and the sample cell can be seen orientated at $45^\circ$ to the main axis.

Consequently, the light has two components, one (the pump beam) being parallel to the $B_0$ direction, while the other component (the read-out beam) is perpendicular to $B_0$. The $^{87}$Rb is pumped into a preferred quantum level which
aligns the moments parallel to the $B_0$ direction. The angular momentum is transferred to the Xe and Kr isotope nuclei by an exchange interaction, which results in the noble-gas magnetic moments also being aligned along the magnetic field.

![Fig. 6. Litton NMRG.](image)

The orthogonal component of the light produces the intensity-modulated signal required for detection at the photodetector. The quoted drift rate is of the order of $0.05^\circ/h$ and the stated performance goals are contained in Table 3. Mu-metal shielding is used to attenuate the effects of external magnetic fields (a buffer gas, such as $^3$He, is included to reduce cell-wall interactions). As the Litton NMRG uses a single cell–binary species approach, there is a dependence on the gyromagnetic ratios when measuring gyro rotation. NMRG research with a low-cost variant has been undertaken by a German subsidiary, LITEF.

The Singer–Kearfott NMRG variant consists of two sample cells each containing the isotopes $^{199}$Hg and $^{201}$Hg as the nuclear species. The pump beam is derived from a $^{204}$Hg lamp while the read-out beam is generated by a $^{202}$Hg lamp, as shown schematically in Fig. 7(a).

Table 3 summarizes the cell constituencies and operating conditions. Each sample cell resides in an oppositely directed magnetic field from the

<table>
<thead>
<tr>
<th>Species</th>
<th>Pump wavelength (nm)</th>
<th>$\omega_L$</th>
<th>$H_0$</th>
<th>Gas pressure</th>
<th>Spin density</th>
<th>Container</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{199}$Hg</td>
<td>253.7</td>
<td>1 kHz</td>
<td>1.2 G</td>
<td>$10^{-4}$ mmHg</td>
<td>$10^{12}$/cm$^3$</td>
<td>High-quality fused silica cell</td>
</tr>
<tr>
<td>$^{201}$Hg</td>
<td>185.9</td>
<td>169 Hz</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
other. The feature has the useful property that phase variations can be effectively cancelled when the signals from both cells are properly combined. The intensity-modulated signal (using the Faraday technique) is received at the photodetector, where it is amplified and demodulated. The information derived is used to provide the rotational output and supply the feedback signal to maintain a coherent precessional motion of the nuclei. Figure 7 (b) provides a block diagram of the main circuit elements. As in the case of the Litton gyro, mu-metal shielding is required to reduce external magnetic influences. Table 4 compares the Singer–Kearfott goals for their NMRG with those for the Litton version.

**Table 4. Optically pumped NMRG performance goals**

<table>
<thead>
<tr>
<th></th>
<th>Litton</th>
<th>Singer–Kearfott</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias stability</td>
<td>0.1 °/h</td>
<td>&lt; 0.05°/h</td>
</tr>
<tr>
<td>Random wander</td>
<td>&lt; 0.01°/√h</td>
<td>0.015°/√h</td>
</tr>
<tr>
<td>S/N</td>
<td>&gt; 64 dB–Hz</td>
<td>75 dB–Hz</td>
</tr>
<tr>
<td>Relaxation time</td>
<td>300 s</td>
<td>23 s</td>
</tr>
</tbody>
</table>

As the Singer–Kearfott version's regime employs two sample cells in oppositely directed magnetic fields, the gyro rotation should be independent of the ratio of the gyromagnetic constants. Both NMRGs are quite small, being only of the order of 12 cm tall by 10 cm in diameter, with the Litton NMRG the more compact unit.

Naval Air Development Centre NMRG¹⁷ activity appears to be confined to establishing the viability of the NMRG as a low-cost gyro for US Navy aircraft use. Optical pumping, using mercury isotopes, but in a single cell, is used. The NMRG is similar in many respects to that of Singer–Kearfott, but a novel technique is employed to improve the homogeneity of the magnetic field, which has been maintained to within 9 × 10⁻⁴ G using a parallel-plate magnetic field coil (additionally, conventional mu-metal shielding is also employed to assist in the
exclusion of external influences). The ‘stabilizing’ coil consists of eight smaller coils symmetrically placed around the perimeter of the plate (with the cell block, NMR resonance cell and other components inside) and which generates the homogeneous d.c. magnetic field. The small coils have adjustable ferrite cores for fine tuning. Transverse pumping and Faraday read-out are used.

Presently, drift rates for this version of an optically pumped NMRG have been quoted at between 0.1°/h to 0.2°/h, and it is acknowledged that an order-of-magnitude improvement will be required if the NMRG is to meet the US Navy strapdown requirements. Work is continuing on this NMRG and, as far as can be discovered, it appears to be the sole survivor of a number of NMRG research and development programmes inaugurated in the US during the 1960s and 1970s.

$^3$He cryogenic NMRG. The all-cryogenic approach to establishing an NMRG invariably employs $^3$He as the nuclear species, cooled to liquid helium temperatures (4.2 K). Helium 3 has the advantage of being the only usable substance which is still a gas at these temperatures. A particular disadvantage is the need to maintain the gas at a high pressure (typically 7–8 atm) to achieve a reasonable spin density, a requirement which tends to militate against achieving the requisite values for the relaxation times. Some form of solenoid surrounding the sample cell (with its polarizing and sensing coils) provides the steady $B_0$ flux. The NMR process can then be stimulated by a number of standard techniques (d.c., c.w. or pulse).

The maintenance of a highly homogeneous, temporally stable magnetic field is of crucial importance in realizing a practical cryogenic NMRG. In earlier techniques, Helmholtz coils were employed to provide an approximate cancellation of Earth's magnetic field so that the solenoid–applied field was then known to first order, both in magnitude and direction. Homogeneity was then achieved by using a superconducting cylinder (usually Nb or Pb) around the sample and coils, with the added bonus that such a cylindrical shield (through the Meissner effect) is a very efficient method of excluding external magnetic fields and helps create the very necessary temporal stability of $B_0$. The optically pumped NMRGs did not employ cryogenic superconducting shields as a means of excluding external fields (mu-metal screening was instead used); the experimental system patented by Stanford University¹⁸ was an exception, and is shown schematically in Fig. 8(a), with $^3$He/$^4$He as the nuclear species. The steady flux ($B_0$) is applied, using a set of superconducting coils. Wall-induced relaxation processes were identified as significant in any successful NMRG concept. Steps were taken to reduce the former by using either solid H$_2$ as the wall coating or $^4$He gas as the so-called ‘buffer-gas’. Relaxation times of the order of days appear to have been achieved with the $^3$He/$^4$He gas mixture. Such long relaxation times are indicative of the excellent homogeneity achieved with the superconducting shielding, as can be seen schematically in Fig. 8(b).

Stanford University¹⁸ also experimented with a novel technique for reducing the trapped field to very low levels, on the principle that low fields gave low gradients. By collapsing thin superconducting foils inside the enclosure with the trapped field, low-field gradient environments of the order of $10^{-8}$ G/cm could
be obtained. In addition, very good field stability was also achieved, of the order of $10^{-9}$ to $10^{-10}$ rad/s ($-2 \times 10^{-4}$ to $2 \times 10^{-5}$ deg/h).

Cryogenic NMR Research at ARE (Slough) to date (see Ref. 1) has concentrated on an all-cryogenic approach using $^3$He gas at 4.2 K as the nuclear species and incorporating an accurately machined niobium cylinder as the means of enclosing a highly homogeneous magnetic field and excluding external magnetic fluctuations. NMR signals are detected by an r.f. superconducting quantum interference device (SQUID). Figure 9 illustrates the essential features of the cryogenic methods involving superconducting cylindrical shields. In Fig. 9(a), the $^3$He gas sample is at 4.2 K, with the solenoid external to the shield providing the flux $B_0$, as used
Fig. 10. Basis for an all-cryogenic NMR gyro (ARE (Slough) 1985).

at ARE (Slough). The solenoid initially carries a current establishing $B_0$. The temperature is lowered until the shield becomes superconducting. The coil current is switched off, thus trapping a homogeneous temporally stable field. Figure 9(b) is an extension of the principle except that room-temperature NMR (i.e. proton magnetometry) is now possible because of the internal Dewar system. This arrangement has been used by ARE (Slough) to explore the effects of the superconducting cylinder and its supercurrent on the NMR signals, with the aid of a commercially available proton magnetometer (Littlemore Type 820) in which the combined polarization/sensing coil is immersed in hexane (the source of the...
protons). Figure 9 (c) represents an optically pumped arrangement in which the nuclear species is a low-pressure $^3$He gas at room temperature, and is similar in principle to the experimental technique of Sussex University.

Figure 10 shows the main elements of the ARE (Slough) cryogenic experimental apparatus exploring rotation-rate sensing, showing the pulsing and sensing coils, all enclosed within the Nb cylindrical shield. The entire assembly is immersed in liquid helium at 4.2 K as the coolant and contained within a cryostat (which has an outer jacket containing liquid nitrogen and an array of appropriately engineered radiation baffles). A copper solenoid surrounds the Nb cylinder and applies the $B_0$ field parallel to the cylinder axis. This field is first applied when the Nb cylinder has been cooled to around liquid N$_2$ temperatures but is still in the non-superconducting phase. Cooling is continued until 4.2 K is reached, by which time the Nb cylinder has become superconducting (at about 9.3 K for Nb). The externally applied $B_0$ field is then switched off. Due to the superconducting nature of the Nb cylinder and the Meissner effect, a magnetic field equal to the sum of the $B_0$ field and the value of the Earth’s magnetic field as the cylinder went superconducting remains trapped within the cylinder. The so-called ‘90°-pulse’ technique is employed to induce magnetic resonance in the $^3$He sample. The characteristics of the pulse (frequency, amplitude and duration) must be chosen carefully to correspond with the NMR frequency as a consequence of the value of the trapped field and the slight uncertainty due to the contribution from the Earth’s magnetic field. The trapped field is in the region of 4 G, giving an NMR frequency around 13 kHz. With the aid of a spectrum analyser, the NMR signal is invariably observed in the region of 13 kHz. The exact value is unimportant provided it can always be determined with the requisite degree of precision. However, continuing progress has been hampered by a low S/N ratio and a short $T_1$ (usually less than a second), and a number of modifications are being implemented to ease these difficulties. The purity of the $^3$He is paramount, the main impurities being O$_2$ and water vapour. Glass-cleaning techniques (and the use of cold traps) are being improved.

A foremost consideration is the reappraisal of the magnetic shield design. The closeness of the shield to a true cylinder has been assessed by microwave cavity resonator techniques and tolerances were found to be satisfactory. Precision metrology by the National Physical Laboratory (NPL) using cryogenic techniques has indicated some important points on the behaviour of the cryogenic shield. To date, ARE (Slough) use a simple hollow cylinder of Nb as the shield; NPL have found the use of two concentric superconducting shields (outer of lead, inner of Nb) to greatly improve the shielding properties. Furthermore, the manner in which the shields become superconducting has a very marked influence on the degree of homogeneity of the trapped field. For example, the outer shield should be cooled from the base to the top and from the inner edge to the outer edge, and to ensure that this occurs NPL use a good thermally conducting baseplate (e.g. copper) attached to the inner edge. It has long been recognized that optically pumped NMR enjoyed a number of advantages over any all-cryogenic method, namely, greatly improved S/N ratio and longer relaxation times. Until the contract was awarded to the School of Mathematical and Physical
Sciences, Sussex University, there had been no optically pumped NMRG based on low-pressure, room-temperature $^3$He gas as the nuclear species. It is also planned to employ a superconducting shield, although initial measurements to establish the viability of the technique used Helmholtz coils to provide a sufficiently homogeneous magnetic field. Optical pumping has been successfully demonstrated in $^3$He, with a nuclear polarizability in the region of 7 per cent and a $T_2^*$ relaxation time in excess of 130 s.

Figure 11 shows the proposed arrangement which will include the superconducting shield (the optical pumping and detection regime is the same as for the Helmholtz coils arrangement without any cryogenics). An important experimental detail is the special annular cryostat, which will be required to accommodate the superconducting shield. Preliminary results with a superconducting shield show that NMR is possible inside the shield but that the relaxation times are considerably shorter (15 s). Presumed defects in the shield, and a method of cooling the shield, are thought to be responsible, and the shield-cooling method is being altered to provide a greater degree of field homogeneity. Attention will also be paid to the precise design of the double cell, in which pumping is performed in one cell and NMR in the other. The most recent development is that the system now behaves as an optically pumped 'maser', so that as long as pumping is continued a continuous read-out of the NMR signal is available.

![Diagram of Sussex University NMR system, showing optical pumping of $^3$He.](image)
CONCLUSIONS. That the nuclear magnetic resonance gyro is a practical possibility has been amply demonstrated by Litton and Singer–Kearfott, where the former have produced a prototype single-axis optically pumped NMRG only about 8 cm in diameter by 10 cm high, with a drift-rate no worse then 0.05° per hour. Both organizations have now ceased all activity on NMRG developments, although a subsidiary of Litton in West Germany is still undertaking some research. Singer–Kearfott are reported to have sold their technological rights to French and Israeli interests.

Discussions with Litton Systems Inc., California, have highlighted the main reason for discontinuing development of the NMRG. The maturing of fibre optic gyros and, particularly, RLG technology, has made the electro-optic approach to rotation sensing more attractive, especially when the US funding agencies share the same view. It was obvious from the conversation that NMRG development was discontinued only rather reluctantly, the programme having stopped as little as 2½ years ago. Litton are aware of ARE (Slough) activity and the use of the superconducting shield. It is their opinion that this approach remains a viable method of improving field homogeneity and stability and they have proffered their encouragement to ARE (Slough) to continue.

During the discussion an interesting point was mentioned by Litton; they found that their version of the NMRG appears to possess a very low dynamic range (the programme was cancelled before this aspect could be explored in detail). Conceptually, a possible reason for such a phenomenon might be the low viscous drag between the bulk of the gas and the sample container walls. If the system were rotated rapidly about an axis of rotation coincident with the central axis of the gas sample, there is no guarantee that the bulk of the gas would rotate when the same cell rotated. Litton suggest that the NMRG may best be operated as a form of rotation null sensor on a set of gimbals rather than in a strapdown mode requiring a high dynamic range. Therefore, the future programme for NMRG research and development should retain the superconducting shield method of producing the required field homogeneity (as well as acting as a very efficient screen to exclude external field fluctuations). Other improvements will include an increased polarizing field (e.g. 200 G) using a solenoid inside the superconducting cylinder. An improved \( S/N \) ratio should result. Whether the all-cryogenic approach should continue is rather more doubtful, particularly when the advantages of optical pumping are considered. Particular aims must be to further improve the \( S/N \) ratio (d.c. SQUID) and achieve longer relaxation times (use of \(^3\)He/\(^4\)He mixture with \( \text{H}_2 \) wall coating, at a low pressure if possible). Finally, Fig. 12 represents the essential characteristics governing the realization of a practical NMRG. Assuming that relaxation times of the order of 100 s are possible, to achieve drift rates no worse then \( 0.01^\circ/h \) a \( S/N \) ratio of 30 db is required (assuming \( f_{\text{NMR}} = 10 \) kHz or 40 db-Hz), parameters currently believed quite feasible. If such a gyro can be developed at a low cost, the NMRG will continue to remain a contender for SLINS. Now that the programme at ARE (Slough) has become better-staffed, useful progress is expected within the next 12 to 18 months; the ARE NMRG is alive and well, if a little starved of nourishment.
NO. 3 NMRG: A REVIEW

Fig. 12. S/N density and relaxation time parameter for an NMRG.

REFERENCES


