The Choice of Criteria and Methods to Estimate the Quality of the Angular Sensor Based on the Effect of Nuclear Magnetic Resonance

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Abstract. To adjust the stabilization systems that ensure the operation of the angular position or rate sensor based on the effect of nuclear magnetic resonance, it is required to choose the criteria for the quality assessing of sensor's operation. The article presents the criteria of the quality of the angular sensor operating as a self-oscillation system. It is shown that the accuracy of the angular sensor increases when the proposed criteria are met.

Introduction
An angular position or rate sensor based on the effect of nuclear magnetic resonance (hereinafter referred to as the angular sensor) allows measuring angular displacements. The angular sensor uses spin-exchange pumping of isotopes of inert gases and optical detection of their condition [1]. The accuracy of the measurement of angular displacements is determined by a variety of factors [2], and for this reason a large number of control and stabilization systems should be implemented in the design of the angular sensor, which have a strong cross-effect on each other [3]. When adjusting each of the above-mentioned stabilization systems, it is necessary to determine their impact on the quality of the angular sensor operation and on the accuracy of its information signal. To determine the accuracy of the angular sensor, it is necessary to carry out long-term measurements, which complicates and slows down the process of adjusting the stabilization systems. Thus, an urgent task is to formalize the criteria that determine the quality of the angular sensor operation without assessing the accuracy of its information signal production in order to adjust the parameters of its stabilization systems.

1. How the angular sensor works
The angular sensor's functional scheme is shown in Figure 1. The main node of the sensor is the spin generator [3], which produces signals corresponding to the precession of the two xenon isotopes 129Xe and 131Xe. These signals are fed to the inputs of two lock-in amplifiers LA-A and LA-SS. The signal of the precession of xenon 131Xe isotope is fed to the input of the LA-A, and the signal of the product of two precession signals is fed to the input of the LA-SS. The signal at the output of LA-A is fed to the entry of the low frequency filter (with a cut rate of 10 Hz) LPF-1 at the output of which a
signal is produced with a frequency corresponding to the sum of two frequencies of xenon isotope generation. This signal is fed to the inputs of the PID controller PID-SS, which produces a control current for the field stabilization system in the coil Z. The coil Z sets the magnetic field $B_0$ and $B_{AC}$.

![Diagram](image.png)

**Fig. 1.** The scheme of the angular sensor based on the effect of nuclear magnetic resonance

The signals of the rotation of polarization plane from two lock-in amplifiers LA-X and LA-Y are fed to the entry of the two PID controllers PID-X and PID-Y respectively for extracting DC signals to compensate the DC components of magnetic field by the coils X and Y [4]. The difference between the spin generator shown in Figure 1 and the spin generator presented earlier [3] is that the xenon isotopes $^{129}$Xe and $^{131}$Xe precession signals are supplied separately to the coils X and Y. The
projection of the xenon isotope 129Xe precession signal along the Y axis is supplied to the coil X; and 131Xe precession signal projection on axis X is supplied to coil Y. Coil Y in figure 1 is not shown. It is located at a 90° angle relative to the coil X.

In addition to the systems described above, the angular sensor includes the systems for generating and stabilizing the radiation pumping and detecting, the temperature stabilization system of optical pumping and detecting emitters, and the temperature stabilization system of the gas cell [5], and the angular sensor case. At the end of the implementation of these algorithms and the receipt of the angular sensor's stable operation, various criteria for assessing the quality of the sensor as a whole have been developed, the most effective of which are the two following criteria: the minimum value of the gain factor at the feedback loop and the magnitude of the phase shift of the two isotope precession components.

2. Minimum of the gain factor at the feedback loop

As presented above, the main node of the sensor is the spin generator, which can be represented by two self-oscillation systems [3], each of which is in stationary self-oscillation operation mode, i.e., all transition processes are completed and the auto generator generates vibrations with frequency $\omega_0$, which is determined by the resonant frequency of xenon isotopes.

One of the main characteristics of such systems is the quality factor of the self-oscillation circuit, which can be written as the ratio of the resonant amplitude to the static amplitude $Q = \frac{A_{\text{resonant}}}{A_{\text{static}}}$. Since the spin generator contains automatic gain control units AGC$^{129}$Xe(Y) and AGC$^{131}$Xe(X) [3, 6], the quality factor of the oscillating circuit can be represented as

$$Q = \frac{A_{\text{stat-set}}}{K_{\text{AGC}} A_{\text{static}}},$$

where $A_{\text{stat-set}} = K_{\text{AGC}} \cdot A_{\text{resonant}}$ is static-set amplitude at the gain control unit's exit; $K_{\text{AGC}}$ is the AGC gain factor generated by the automatic gain control unit.

Accordingly, with a minimum value of $K_{\text{AGC}}$, the quality factor of the self-oscillation system will have a maximum value. In other words, the lower the generated $K_{\text{AGC}}$ value, the better the quality of the generator's operation. As an illustration of the application of this criterion, let's look at the example of optimizing the frequency of detection radiation. The sensor contains two following emitters: an emitter that forms laser radiation for optical pumping of cesium vapor and an emitter that forms laser radiation to detect the condition of isotopes of xenon. The frequency of laser radiation for the optical pumping is chosen such that it is at one of the absorption peaks of the D1 133Cs line, as shown in Fig. 2. The implementation of the algorithms for the frequency locking and stabilizing system of the optical pumping laser is easily formalized.

The implementation of the algorithms for the frequency locking and stabilizing system of the optical detection laser is difficult to formalize when using only information on the absorption level of 133Cs. The algorithms for the frequency locking and stabilizing system of the optical detection laser are well formalized when using information about the generated AGC gain factor value. Figure 3 shows the AGC gain factor value depending on detuning of the detection laser radiation frequency from the pump laser radiation frequency.

According to this graph, the optimal detection frequency detuning is in the area of 15.5 GHz. Using this criterion allows you to constantly monitor the change in the deviation from the optimum of the frequency of laser detection radiation due to changes in the temperature of the gas cell and the crystal of the laser emitter.
Fig. 2. The absorption peaks of the D1 133Cs line (the area of possible frequencies of laser detection radiation).

Fig. 3. AGC gain factor value dependency graph for "Xe^{129}(Y) precession" signal on the detection frequency detuning.

Figure 4 shows a graph of the angle error at the optimal adjustment of the detection laser radiation frequency. The optimal detuning of the frequency is determined by the minimum ratio of the AGC gain factor. Figure 5 shows a graph of the angular error when the laser's radiation frequency is not optimal.
3. The magnitude of the phase shift of two components of isotope precession

Phase balance is one of the conditions of operation of the self-oscillation system [3]. The feedback circuit of the angular sensor contains shift buffers and phase filters (blocks SB\(^{129}\text{Xe}(\text{Y})\), SB\(^{131}\text{Xe}(\text{X})\), APF\(^{129}\text{Xe}(\text{Y})\), APF\(^{131}\text{Xe}(\text{X})\)) to ensure phase balance. High requirements for phase delay in self-oscillation loops must be met to ensure the required accuracy in determining the angle of rotation. Precession signals of each of the xenon \(^{129}\text{Xe}\) and \(^{131}\text{Xe}\) isotopes are generated by processing the output of the LA-X LA-Y lock-in amplifiers. The reference signal input to the lock-in amplifier LA-X is phase shifted by 90° with respect to the signal input to the lock-in amplifier LA-Y. In the generation mode, one lock-in amplifier allows observing a harmonic signal caused by rotation of the magnetization vector of xenon isotopes, and another lock-in amplifier detects a harmonic signal caused by a forced phasing magnetic field. The force field is created by magnetic coils X and Y. The precession phase of xenon isotopes is shifted by 90° relative to the force field phase. Thus, in the self-
generation mode, the phase shift between the signals "Xe (X) precession" and "Xe (Y) precession" will be 0° or 180°. After the generation mode is turned off, free precession of xenon isotopes occurs. In this mode, the phase shift between the signals "Xe (X) precession" and "Xe (Y) precession" will be 90°.

With optimal self-oscillation mode, the phase shift between the signals "Xe (X) precession" and "Xe (Y) precession" should be 0° or 180°. Figure 6 shows the graphs of the signals "Xe129 (X) precession" and "Xe129 (Y) precession" in the self-oscillation mode and immediately after it is turned off. Figure 7 shows the graphs of the signals "Xe131 (X) precession" and "Xe131 (Y) precession" in the self-oscillation mode and immediately after it is turned off.

Fig. 6. The plot of the precession signal of the xenon isotope 129Xe in the self-generation mode and immediately after its stop. (1 - "Xe129 (X) precession" signal, 2 - "Xe129 (Y) precession" signal, 3 - "B129Xe" signal, which is supplied to coil X).

Fig. 7. The plot of the precession signal of the xenon isotope 131Xe in the self-generation mode and immediately after its stop. (1 - "Xe131 (X) precession" signal, 2 - "Xe129 (Y) precession" signal, 3 - "B131Xe" signal, which is supplied to coil X).
Conclusion

Here are two criteria for assessing the quality of the angular sensor as a whole:

- minimum value of the AGC gain factor, this criterion can be presented in the form of
\[ \min(K_{\text{AGC}}) \neq 0. \]

- the magnitude of the phase shift of the two isotope precession components, which can be presented as
\[ \tan(\varphi_{\text{precession}}) = 0. \]

The above criteria allow for assessment of the quality of the angular sensor as a whole. The angular sensor stabilization systems must be adjusted to take these criteria into account. It is also shown that a twofold increase in the accuracy of the angular sensor can be achieved due to the optimal detuning of the detecting laser radiation frequency.

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