Q-MULTIPLICATION FOR INCREASING NUCLEAR MAGNETIC RESONANCE SIGNALS*

By R. Chidambaram

(*Department of Physics, Indian Institute of Science, Bangalore*-12)

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1. Introduction

In a nuclear magnetic resonance experiment, when the coil containing the sample is resonated by a capacitor and the circuit fed from a constant current source, the voltage drop across the coil is given by the approximate relation

$$v \simeq v_0 [1 - i\, 4\pi \mathrm{Q} f \chi],$$

assuming $|4\pi \mathrm{Q} f \chi| \leqslant 1$. Here v_0 is the voltage far off nuclear resonance, Q is the quality factor of the circuit, χ is the complex r.f. nuclear susceptibility and f is the filling factor representing the fraction of the coil's magnetic energy stored in the sample. We note that both the absorption and dispersion components of the nuclear magnetic resonance signal are proportional to the Q of the circuit.

Due to skin-effect, the dielectric losses in the coil form and the presence of a metallic shield round the coil, the values of Q attained by experimenters in this field have rarely exceeded 250, a common value being about 100.

While improvements in the mechanical and electrical design of the coil are not likely to be of much help, it is possible to increase considerably the effective Q of the circuit by the use of an active network to supply energy to the tuned circuit to compensate for its losses. This can be achieved by introducing a shunt negative resistance in parallel with the coil.

2. Principle of Q-Multiplication

If we assume that the shunt resistance of the tuned circuit at resonance is R and that a negative resistance $-\mathrm{R}_n$ is introduced in parallel with it, the effective shunt resistance becomes

$$\frac{\mathrm{R}\mathrm{R}_n}{\mathrm{R}_n - \mathrm{R}} \cdot$$

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This corresponds to a multiplication of the original Q of the circuit by the ratio

$$q \equiv \frac{Q_{eff}}{Q_0} = \frac{R_n}{R_n - R}\,.$$

The Q-multiplication can in principle be made arbitrarily large by letting R_n approach R. If positive feedback is introduced through the resistor R_f from an amplifier of gain A and internal resistance R_i (*see* Fig. 1), it can be easily shown that

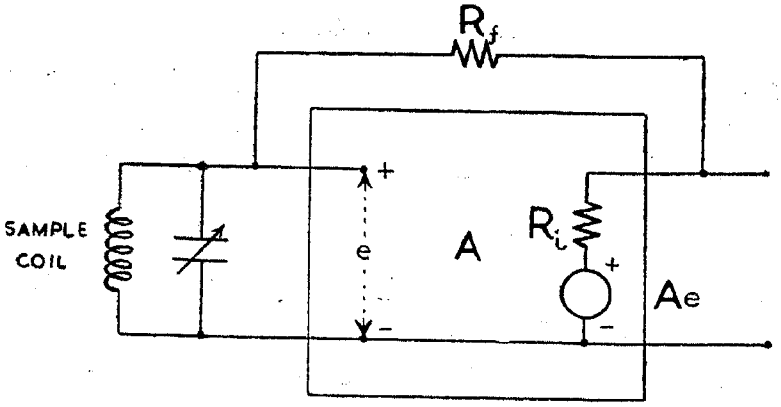

FIG. 1. Basic circuit of the Q-multiplier using shunt negative resistance.

$$-R_n = -\frac{R_f}{A-1} - \frac{R_i}{A-1}\,,$$

assuming the input impedance of the amplifier to be large compared to the other circuit resistances. As the circuit will break into oscillations when R_n becomes equal to R, the gain of the amplifier has to be stabilised by a high degree of negative feedback (Ginzton, 1945) and a high stability resistor has to be used for R_f.

3. NUCLEAR MAGNETIC RESONANCE EXPERIMENTS WITH A Q-MULTIPLIER

Experiments on proton resonance in a sample of water, treated with ferric nitrate solution, were conducted with the amplitude bridge (Thomas and Huntoon, 1949). A Q-multiplier of the type described by Harris (1951), which employs a single tube acting as a cathode follower in the feedback path, and consequently has a high inherent stability, was used. A minor modification to the Q-multiplier involved the application of feedback to the junction between two fixed capacitors connected in series across the main tuning condenser instead of splitting the latter. The complete circuit is given in Fig. 2. A brief analysis of the circuit, neglecting stray capacitances,

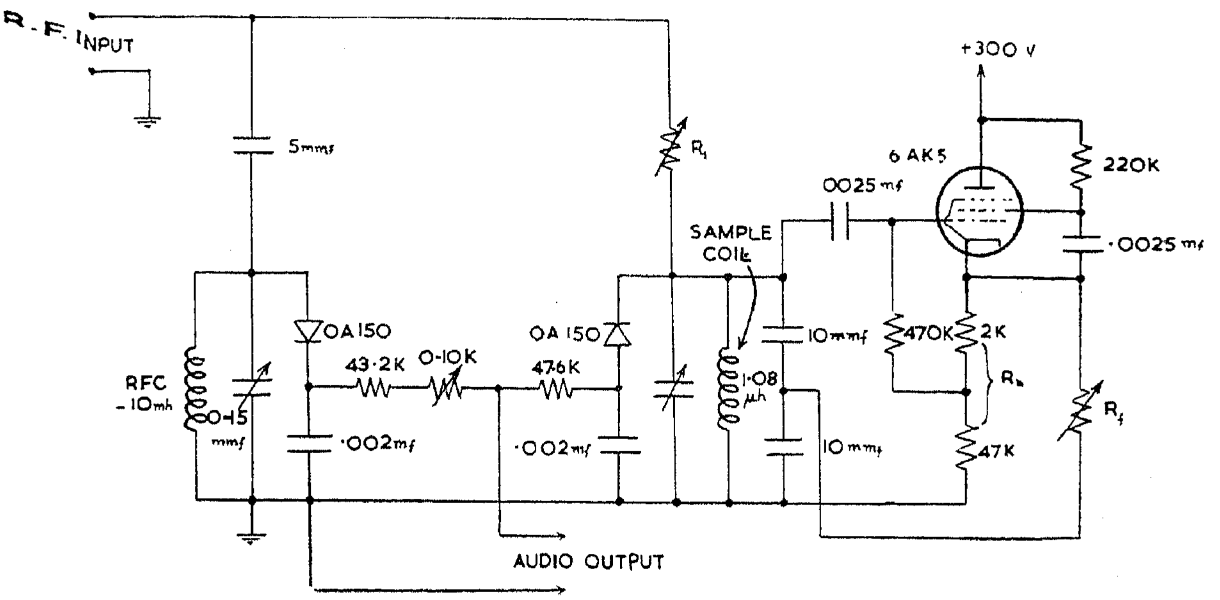

FIG. 2. Amplitude bridge with a Q-multiplier.

shows that the effective negative shunt resistance introduced across the coil is

$$-R_n = -4 \cdot \frac{R_k r_p + R_f \{(\mu + 1) R_k + r_p\}}{(\mu - 1) R_k - r_p},$$

where r_p and μ are respectively the plate resistance and amplification factor of the tube.

The variable resistance R_1 served to maintain a given voltage across the coil for different effective values of Q. At a frequency of 7·35 Mc./S., a maximum increase in signal strength by a factor of about 5 was observed. The Q-multiplication achieved was limited because the shunt resistance of the tuned circuit (about 3,500 Ohms) was smaller than the magnitude of the minimum shunt negative resistance that could be generated by this simple Q-multiplier. It is, however, ideally suited for work in low field NMR spectroscopy, for the shunt resistance of the tuned circuit encountered there is quite high, a typical value being 780 KΩ at 50 Kc./s. (Brown, 1950). At frequencies of the order of a few megacycles, it is desirable to use an amplifier with a stabilised gain of about 10.

Another design criterion that has to be borne in mind at high frequencies is to satisfy the condition that the circuit be fed from a constant current source even at high values of the Q-multiplication factor for maximum benefit. A 0·1 mmf. capacity between the r.f. input point and the terminal of the tuned circuit at 20 Mc./s. corresponds to a reactance of about 80 KΩ whereas the effective shunt resistance of the tuned circuit at a Q_{eff} of 5,000 may be of the order of 200 KΩ. This difficulty does not arise in the nuclear induction method of resonance detection (Suryan, 1958).

4. DISCUSSION

Q-multiplication can enable effective Q's of the order of 10,000 or more to be achieved without undue difficulty. This will lead to a hundred-fold or even greater increase in the strength of nuclear magnetic resonance signals.

If q is the Q-multiplication ratio, it may appear from the formula of Bloembergen *et al.* (1948) that, for a detecting system whose band width is determined by the final phase-sensitive detector, the signal-to-noise voltage ratio should also increase by a factor $\sqrt{q}$. This is, however, not so because both the nuclear magnetic resonance voltage and the thermal noise voltage generated in the sample coil are affected equally by the feedback. But the amplifier noise at the output will be somewhat less due to the lower amplification now required. There might also be a slight improvement for an oscillographic display due to the increased selectivity of the circuit.

Recently Benoit, Grivet and Guibé (1958) have independently appreciated the advantage of increasing Q by positive feedback in the design of a maser based purely on nuclear magnetic resonance.

5. SUMMARY

A method of increasing the strength of nuclear magnetic resonance signals by factors up to 100 or even more is suggested. The principle is to increase the quality factor Q of the coil containing the sample by means of positive feedback. Experiments on proton resonance in water, treated with ferric nitrate solution, using a Q-multiplier with the amplitude bridge, are described.

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