Chapter V

AN INNOVATIVE MAGNETIC FIELD SWEEP UNIT

Abstract

The chapter begins with a consideration of the basic requirements for the magnetic field sweep used in NMR experiments. The earlier field sweep circuits and their drawbacks are briefly mentioned. Following this, an electronic magnetic field sweep circuit, that functions as a separate unit, is described in detail. The design and fabrication of an improved electronic field sweep system which generates almost perfectly linear field sweeps is then discussed. At the end of the chapter the performance of the improved field sweep unit and its various advantages over the earlier systems are highlighted.

5.1 : Basic requirements of the magnetic field sweep

For the recording of the NMR signals the magnetic field has to be swept linearly at a slow but well-defined rate over a small range which is usually a few times the width of the resonance line under investigation. For getting accurate and faithful recordings the field sweep should be perfectly linear over the time interval required to record the whole signal. A non-linear field sweep will pose several problems, as a result of which the recorded signal will no longer be a true reproduction of the actual signal shape. Beside the second moments calculated under this situation will hardly be accurate enough to be useful.

An appropriate sweep rate has to be selected that permits undistorted recording of the NMR signal, within a convenient duration of time. At very rapid sweep rates the nuclear magnetic moment will not be able to follow the sweep field, which then will lead to considerable distortion in the lineshape. For recording single scan spectra the best procedure is to use the lowest possible sweep rate [1].

5.2 : Earlier field sweep methods

The magnetic field sweep is conventionally effected by varying the reference voltage of the magnet current stabilizer within a prescribed range and at a desired rate using mechanical arrangements [2, 3, 4, 5, 6]. A magnetic current stabilizer which incorporates this field sweep arrangement is symbolically represented by the block diagram of Fig.5.1. In actual practice a small d.c. voltage, that can be scanned in the desired manner, is combined with the actual reference voltage and the resultant voltage is given as the effective reference signal to the comparator circuit of the current stabilizer. A typical circuit used to effect this is shown in the schematic diagram of Fig.5.2. The voltage selected by the potentiometer P₁ forms the main reference voltage. (P₁) also permits manual scanning of the magnetic field. The battery B may be a low value standard cell. 'R' essentially stands for a resistance selector circuit. P₂ is a wirewound precision potentiometer, the centre spindle of which is driven by a synchronous motor and reduction gears. By changing the gear ratio the sweep rate can be varied, while a suitably selected R value will provide the required field sweep range [4, 5]
Fig. 5.1: Block diagram of a magnetic current stabilizer incorporating field sweep
Fig. 5.2: Schematic circuit of a reference voltage sweep setup

Highly regulated reference voltage unit

Low d.c. voltage scanning section
However the mechanical field sweep system possess several inherent drawbacks including electrical noise produced by the movement of the slider on the potentiometer, the eventual degeneration of the potentiometer through wear, etc.. With prolonged use these potentiometers will become excessively noisy and the sweep will no longer be steady. The overall flexibility of the system is very poor, as any desired change in sweep rate is very difficult to implement.

5.3 : An electronic magnetic field sweep unit

The mechanical field sweep systems can be replaced with more convenient electronically controlled field sweeps which can be made highly flexible as well as reliable. In one system [7] an op-amp integrator circuit generates a sweep voltage which is used to vary the reference voltage of the control unit of the magnet current stabilizer to effect the field sweep. But in this case there exists a possibility for interaction between the sweep circuit and the current control unit which may lead to unwanted fluctuation and noise.

With a view to eliminate the inherent limitations of mechanical field sweep systems and also to avoid any unwanted interaction between the sweep circuit and the current control unit a new electronic magnetic field sweep unit has been designed and fabricated [8]. This system functions as an entirely separate unit without any interaction with the magnet's main current control unit. At the same time, due to the sufficient amount of d.c.amplification which is provided in this circuit, considerable output current can be derived to cover the required field sweep range.

5.3.1 : Description of the field sweep unit

The field sweep unit designed here is symbolically represented by the block diagram of Fig. 5.3. Essentially it consists of three main sections: (i) a generator of linear sweep voltage, (ii) d.c.amplifier stages for enhancing the sweep signal to the required output power level and (iii) the magnetic field sweep generator coils. Besides these is a regulated power supply section for energizing the different sub-assemblies. The actual circuit of the field sweep unit is shown in Fig.5.4.

(i) Sweep voltage generator:- The sweep voltage generator is basically an op-amp integrator circuit with provision to choose sweep speeds as required. The integrator output is given by the relation,

\[ V_0 = \frac{1}{(RC)} \int V_i \, dt. \]

If the input voltage \( V_i \) is constant the op-amp will start integrating the input voltage with a time constant \( (RC) \) till the voltage reaches a saturation value \( V_{0_{\max}} \) determined by the supply voltage (and the limiting values of the op-amp characteristics) in a time \( T_s \) given by

\[ T_s = \frac{V_{0_{\max}}}{(V_i)} (RC) \]

Evidently the sweep speed can be varied by changing the value of \( V_i \) or \( (RC) \).

In the present circuit an LM 741 op-amp functions as the integrator \( A_i \). The time constant is chosen to be 10 seconds. Sweep speed is selected by changing \( V_i \) by means
Fig. 5.3: Block diagram of the field sweep unit
Fig. 5.4: Schematic circuit of the electronic field sweep unit
of the potential divider $P_1$. Sweep speeds can be varied in steps by a factor of four each from 0.5 to 128 minutes. The potential divider $P_2$ is so chosen that after d.c. amplification the final output when applied to the sweep coils can give magnetic field sweep variations by a factor of two each in steps from 5 to 80 gauss.

The $1\Omega$ resistor connected between the non-inverting input of $A_1$ and the circuit ground helps to reduce the effect of input bias current in the integrator. For greater advantage the op-amp $A_2$ should be one having high-gain, low-offset voltage and low-bias current. Chopper-stabilized amplifiers will be an ideal choice, especially because of their superior long-term d.c. stability.

The $10\mu F$ integrator capacitor should be one having very low leakage, like a polystyrene or tantalum capacitor. The $1\Omega$ integrating resistor as well as resistors in the output and sweep input attenuators should possess very good stability.

(ii) D C amplifying stages: - The d c amplifying section consists of an op-amp buffer followed by three stages of current boosters. The op-amp $A_3$ provides the necessary stability to the sweep signal before being subjected to current boosting by the Darlington pair consisting of the transistors $Q_1$ (BC 107) and $Q_2$ (SL 100). The final power amplification is effected by the power transistors $Q_3$ and $Q_4$ (2N 3055s).

A diode $D_1$, connected between the base of $Q_1$ and emitter of $Q_2$, serves to stabilize the current through $Q_2$ and thus preventing it being overdriven. At the same time $D_1$ keeps the base of $Q_1$ and emitter of $Q_2$ well isolated. The diode helps to prevent any positive feedback to $Q_2$ from the load side.

The highly regulated $+15V$ and $-15V$ supply voltage for the op-amps $A_1$ and $A_2$ are derived by employing $\mu A$ 723 IC regulators in the high voltage regulator configuration, as shown in Fig.5.5. The $\mu A$ 723 voltage regulator was chosen due to its high ripple rejection and low temperature drift [9]. The $+15V$ regulated supply also powers the transistor $Q_3$. For energizing the power transistors $Q_3$ and $Q_4$, a $+20V$ regulator capable of supplying as much as $2A$ current was required. The series voltage regulation principle was adopted in the design and the fabrication of this regulator unit, which is shown in Fig. 5.6. The same circuit serves to meet the power requirements of the transistor $Q_2$.

(iii) Sweep generator coils: - The sweep generator coils consist of two circular coils wound over aluminium frames that fit closely onto the magnet polepieces. On each coil is wound some 200 turns of 24 s.w.g. copper wire. The two coils are then connected together such that the field due to them is in conjunction. This coil system will produce a magnetic field $\sim 80$ gauss when a current $\sim 0.6A$ passes through them.

The diode $D_3$ across the sweep coils is connected to bypass any voltage transients at the load and thus to protect the power transistors $Q_3$ and $Q_4$. The $2.7K\Omega$ resistor across the coils provide stabilizing feedback voltage to $A_2$, while the $47K\Omega$ resistor limits the feedback current.

5.3.2: Operation and performance of the field sweep unit

Initially the working of the integrator sweep circuit alone was checked. The sweep voltage was recorded on a chart recorder for the different sweep speed ranges. The
Fig. 5.5: Circuit diagram of the +15V and -15 regulated power supplies
Fig. 5.6: Circuit diagrams of the +20V regulated high current power supply
recordings showed that the output voltage is nearly linear for the fast duration sweeps, while the long duration sweeps were observed to exhibit slight non-linearity.

The integrator was then connected to the d.c. amplifying stages and the sweep coils to constitute the complete field sweep unit. The sweeping of the magnetic field was also tested, using a Hall probe, and was seen to emulate the sweep voltage recordings approximately. The performance of the complete sweep unit was then tested by recording the proton signal in Fe(NO₃)₃ solution. The recording of the signal was fairly satisfactory.

5.4 : An improved electronic linear sweep circuit

As mentioned above the sweeps generated by the field sweep unit of Fig. 5.4 are not perfectly linear. Though the 1/2 min and 2 min sweeps were observed to be nearly linear the long duration sweeps were found to exhibit non-linearity that increases with increasing sweep time. Fig. 5.7 shows a tracing of the 8 min field sweep, from which the non-linearity present is clearly evident.

The non-linearity of the above op-amp integrator sweep was understood to be due to a number of well-known factors [10], the most important of which being the absence of a constant current charging of the condenser in the integrator circuit. It has been found that it is practically impossible to overcome all these factors to get perfectly linear sweeps. Though some circuits claiming better sweep linearity have been proposed recently (e.g. [11]), most of them employ rather complex circuitry with associated difficulties for implementation. This situation has prompted us to design a new circuit that will not only be very convenient to implement but at the same time give almost perfectly linear field sweeps.

The newly designed circuit [12] is an improved version of conventional IC bootstrap ramp generator, in which an appropriately selected op-amp gain is utilised to suppress the various sources of non-linearity.

5.4.1 : Bootstrap sweep generator circuits

The bootstrapping technique is based on the principle that the charging current of the capacitor in a ramp generator can be maintained constant by inserting a source of compensating e.m.f. in series with the charging capacitor. The compensating e.m.f. is supplied by an amplifier whose output voltage is an exact copy of the voltage across the charging capacitor. The circuit utilising this principle is referred to as "bootstrap sweep" circuit since its output voltage is lifted, as it were, by its own bootstraps.

Fig. 5.8 is a symbolic representation of bootstrapping circuit. Here a fictitious variable source v₀ is added in series with the charging voltage V. In the schematic diagram of the circuit shown in Fig. 5.9 the amplifier of voltage gain A generates the variable voltage v₀. Initially v₀ is zero and when the switch 'S' (Fig. 5.9) is open the voltage across the capacitor starts rising towards V. As soon as the capacitor's voltage starts to rise, then v₀ is no longer zero; now the total voltage across the RC combination is V+v₀ and the capacitor aims towards this modified target value. Since the target voltage is constantly increasing, we are always operating in the initial portion of the exponential rise, which is linear. As a result a linear sweep voltage, which emulates the constant current charging of the capacitor, is obtained at the output of the amplifier.
Fig. 5.7: Tracing of the integrator sweep voltage recording corresponding to 8 min (chart speed=3cm/min)
Fig. 5.8: Symbolic representation of a bootstrapping circuit
Fig. 5.9: Schematic diagram of a bootstrapping circuit.
It has been shown [13] that
(i) the sweep speed at the output of the amplifier \( \approx AV/RC \) and
(ii) the slope error of the circuit = \( V_s/V (1-A+R/\sim) \) where \( V_s \) is the sweep amplitude and \( \sim \) is the input impedance of the amplifier.

Fig. 5.10 shows a typical bootstrap ramp generator circuit employing an op-amp A as a voltage follower [9]. Here the high value capacitor \( C_s \) acts as the bootstrapping capacitor, which together with the diode D, serves to establish a linearly increasing charging voltage for the RC combination. At the output of the op-amp a linear sweep voltage is generated.

5.4.2: A modified IC bootstrap ramp generator

It has been observed that the conventional bootstrap sweep circuit incorporating unity gain voltage follower (Fig.5.10) cannot maintain good sweep linearity for different sweep durations. An analysis of the typical bootstrap ramp circuit, as given below, shows that a modified IC bootstrap ramp generator can provide a very much improved sweep linearity.

The slope error of a bootstrap sweep is known to be proportional to \( (1-A+R/\sim) \), \( A \) being the amplifier gain, \( R \) the input impedance of the amplifier and \( \sim \) the charging resistance [13]. This indicates that if a unity gain voltage follower employing a commonly available op-amp is adopted as a bootstrap long-duration ramp generator, then \( R/\sim \) cannot be kept small enough to minimise the slope error. However, if FET input op-amps are used, then in principle one should get perfectly linear sweeps, since then \( R/R_i=0 \). Though this is true to some extent, in practice it has been observed that such perfectly linear sweeps are never generated in the case of circuits employing FET input op-amps like CA 3140 or OPA 121 with unity gain. The reason evidently is due to the non-ideal performance of the remaining components such as charging capacitor, bootstrapping capacitor etc. which contribute to the slope error. The slope error of the bootstrap ramp circuit can then be taken as proportional to \( (1-A+R/\sim+k) \), where \( k \) stands for the contribution to the slope error by components other than the op-amp. Thus one finds that even an FET input op-amp under unity gain condition cannot generate perfectly linear sweeps. If, instead, the op-amp gain is chosen to be greater than unity, as \( A' = 1+(R/\sim+k) \), we see that the slope error will reduce to zero thus eliminating any non-linearity. This was indeed observed by us and we have seen that by carefully setting the op-amp gain the utmost in sweep linearity can be obtained for the desired sweep durations. It appears that an op-amp gain greater that unity serves the dual purpose of keeping the sweep time much less than the RC time constant as well as providing the excess gain required to stretch out the non-linearity of a unity gain bootstrap sweep. Both these factors help to obtain excellent sweep linearity.

5.4.3: Description of the field sweep unit

The field sweep unit incorporating this modified bootstrap circuit is symbolically represented by the block diagram of Fig. 5.11. As in the earlier field sweep unit, the set up essentially consists of three main sections: (i) a generator of linear sweep voltage, (ii) d.c amplifier stages for enhancing the sweep signal to the required output power level and (iii) the magnetic field sweep generator coils. The sections (ii) and (iii) are the same ones that were used in the earlier field sweep system of Fig.5.4, while for the sweep generator section the modified IC bootstrap configuration is used. The actual circuit of the field sweep unit thus fabricated is shown in Fig. 5.12.
Fig. 5.10: Schematic circuit of a typical bootstrap ramp generator
Fig. 5.11: Block diagram of the improved field sweep unit
Fig. 5.12: Schematic circuit of the improved linear field sweep generator.
The modified bootstrap ramp generator forms the first part of the figure. The op-amp $A$, acts as the bootstrapping amplifier while $R$ and $C$ constitute the charging circuit. In this setup the sweep speed at the output will be $A'V/RC$, $V$ being the potential difference across the bootstrapping capacitor $C_t$. The maximum sweep output voltage will then be $V_o = A'VT_s/RC$ so that the sweep time $T_s = VRC/A'V$. Provided that $C$ has a low leakage but high charge capacity, then $V_o$ will approach a saturated value $V$ in a time $T_s = RC/A'$.

The sweep duration can thus be varied by changing $R$ or $C$.

For the present work the circuit has been designed to give sweep durations of 1/2, 5/2, 4 and 8 min by choosing a constant value for $C$ and varying $R$. A low value tantalum capacitor was chosen for $C$ while an ordinary electrolytic capacitor was chosen for $C_t$, which should have a value much greater than $C$. $R_2$ together with $R_1$ sets the op-amp gain required to obtain the utmost in sweep linearity. By trial $R_2$ is adjusted to obtain the best linearity for each sweep duration setting.

The linear sweep voltage is then subjected to proper current boosting by the d.c. amplifying section. On passing this sweep current through a pair of field sweep generator coils the required linear variation in magnetic field is obtained. Variation of the strength of the sweep field can be conveniently done by varying the amplitude of the ramp voltage input to the d.c. amplifiers. In the present case the potential divider $P_2$ provides a magnetic field sweep range from 0.5 to 8 mT (5 to 80 gauss) by a factor of two in successive steps.

5.5: Performance of the improved field sweep unit

The recordings of the sweep voltages for different sweep durations have shown that the output linearity over the entire range is much better than 0.1%. This is evident from Fig. 5.13, which shows the tracing of the sweep recording corresponding to 8 min duration. The linearity of the corresponding magnetic field sweep was also found to be excellent. The performance of the complete sweep unit was then tested by recording the broad proton resonance signals from standard samples like polycrystalline NH$_4$Cl, etc. The recording of the signals were entirely satisfactory.

5.5.1: Advantages of the innovative field sweep unit

The linear magnetic field sweep unit, which uses only commonly available components, gives a much improved performance in comparison with conventional sweep circuits. The modified bootstrap sweep generator circuit adopted here has a notable advantage in that the amplifier gain can be conveniently manipulated to obtain the utmost in sweep linearity for any desired sweep duration. Besides, unlike the earlier circuits (e.g. [7,11] and the one described in section 5.3), a separate DC input is not required here to initiate and maintain the sweep. These advantages make the improved field sweep unit a simple but effective one as required for the recording of wideline NMR spectra. In this context it is worth mentioning that the improved sweep circuit design can as well be utilised in any other application where a highly linear long duration sweep voltage becomes necessary.
Fig. 5.13: Tracing of the improved sweep voltage recording corresponding to 8min duration (chart speed ~ 2cm/min)
REFERENCES