An Application of Digital Signal Processing for Measurements of Cyclic Magnetic Field

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Abstract

In order to monitor a cyclic magnetic field of synchrotron we have developed a digital integration technique which could replace a conventional hardware integration technique. This method provides us an easy and less costly but accurate magnetic monitoring.

1 Introduction

A knowledge of accurate monitoring in synchrotron is useful for manipulating accelerated beam. In the past, excitation current of the magnet rather than the magnetic field is usually monitored. Why is monitoring of the magnetic field is necessary? In some cases, there observed a discrepancy between the current and the magnetic field like in LEP of CERN where return current of TGV bullet train disturbed the beam position. At the KEK booster rapid cycling synchrotron, a flip coil, which is a search coil device capable of flipping by 180 degree along magnetic field direction, is used to monitor an actual magnetic field. It turned out keeping the DC magnetic field constant, the DC bias current drifts away to an appreciable amount due to a temperature change of choke transformer and magnet load. Thus monitoring the magnetic field and sometimes feeding back to a power supply is required for a stable operation of a synchrotron.

In the past, magnetic field is monitored by NMR, a Hall probe, a flip coil and a search coil. Each method has merit and demerit. Among others, the search coil method is the simplest, although only AC component can be detected. The output voltage of the search coil is a time derivative of the magnetic flux and one needs an integration in time. This is usually done by a combination of VFC(Voltage to Frequency converter) or analogue integrator. In the analogue integrator, the hardest part is how to suppress the offset drift of the integrator system.

Compared with the search coil method, NMR is the most accurate method. Its disadvantage is slow time domain response and a high sensitiveness to uniform field distribution. Hall probe system is a handy measurement tool. Its accuracy, resolution and stability is not often good enough for a synchrotron magnet. Stability could be achieved by a high performance temperature controller but improving the resolution at a level of tens of ppm is very difficult.

Instead of developing extremely low drift integrator using operational amplifier, we have chosen a digital integrator system using commercially available high performance FFT(Fast Fourier Transformation) analyzer of wide dynamic range[1]. In this method, the offset voltage in the system is compensated by subtracting the artificial offset. The integration is performed using a built-in function of the FFT analyzer after acquiring the data into the FFT analyzer using the fact that the excitation current of the magnet is repetitive with an enough accuracy. The characteristic feature of our method is a wide dynamic range and no requirement of active element between the search coil and the AD converter thus eliminating frequent offset adjustment which leads to a reliable magnetic measurement.

2 Measurement principle

Synchrotron magnet is operated with periodic cycle. In the HIMAC where the method is applied this period is usually 3.3 seconds. The excitation pattern is synchronized to AC power line by a 1200 Hz clock pulse of power thyristor. The causes of offset voltage in the measuring system are a contact potential difference and contact electricity at cable junctions from the search coil and also at a front end circuit of the FFT analyzer. We used Hewlett Packard HP35670A.

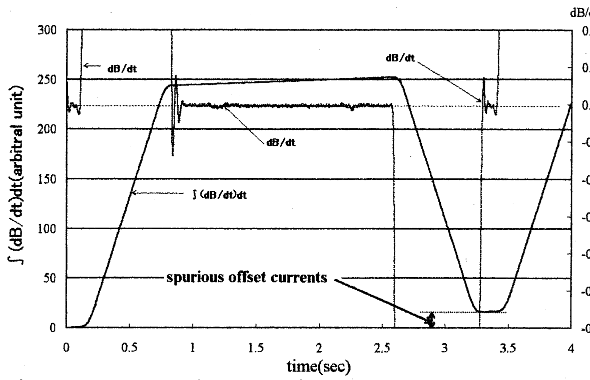

Fig. 1 Output voltage and its integrated voltage without subtracting offset voltage.

The current pattern output from the power supply has a trapezoidal shape. The reproducibility of this pattern is mainly determined by the accuracy of the DCCT. We have used Holec DCCT whose short term accuracy is expected to be around 10 ppm or better. We take an advantage of this high reproducibility for magnet measurement. In Fig.1 we show the effect of the offset voltage to the integration of the output voltage where the output voltage and its digital integration with respect to time is presented. The sequential trapezoidal shape consists of the constant low field portion called flat base, rising portion where beam is accelerated, and a constant high field portion called flat top where the beam is stored and slowly extracted and a decreasing field portion where the magnetic field is reset to the initial field. The whole field pattern has an apparent slope which is due to the integration of offset false voltage. The level of the flat base is also clearly different in the figure. This difference can be compensated by using the built-in function of the HP35670A FFT analyzer. The simplest compensation of the zero-th order can be done in a following way. Denoting the effective area of the search coil as A which is a product of number of turns of a coil N and its area S, A=NS,

$$B(t) = A\int_0^t \{e(t) + e_k\}dt + \Delta B(t) \qquad (1)$$

where e(t) is an instantaneous output voltage of the search coil and the e_k is the compensating offset. The offset voltage is determined such that the two initial portion of the flat base field coincide. Typical voltage of the e_k is 200 μ V or so with a period of 4 seconds.

3 Measurement

The block diagram of the measurement system is shown in Fig.2. The excitation current of the load magnet is always monitored with Holec DCCT to normalize the magnetic field. In this way, a deviation of the magnetic field from the current can be observed which is of our present interest of the field monitoring. The power supplies are synchronized to AC lines and the trigger pulse of the measurement system is also synchronized to it. The isolation of this trigger signal with optical signal helps to diminish a noise in the system.

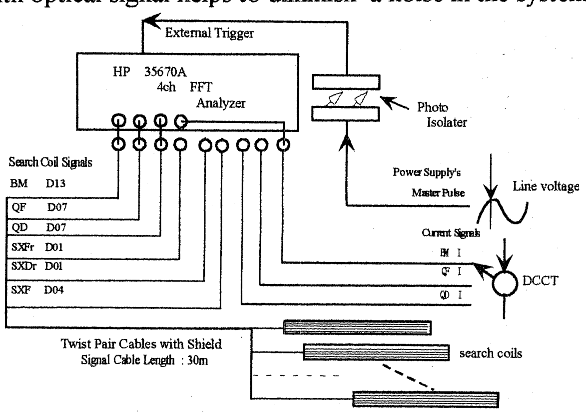

Fig.2 Block diagram of the measurement system

3.1 Target magnet of measurement

The target magnets to be monitored are main bending magnet(BM), horizontally focussing magnet(QF), horizontally defocussinng magnet(QD), sextuple magnet for creating separatrix(SXFr and SXDr), sextuple magnet for chromaticity correction(SXF). The first 3 magnet are excited trapezoidally and the second 2 magnets are pulse excited. The advantage of the search coil method is its easy installation to the magnet in the synchrotron ring contrast to most of other methods where additional monitoring dedicated magnets are prepared.

3.2 Search coil dimension and environment

The search coil dimensions are as follows. The length, L=0.8m, number of turns, N= 26 turns, cross section, S=0.0048x0.8 m^2, wire diameter, d=0.32 mm. The cable is a twisted cable and its length is 30 m long which is a distance from each magnet to monitoring place in the power supply room. The cables are grounded at a single point in the FFTanalyzer side. The setting of the front end of the analyzer is high impedance mode.

4 Measurement Result and Discussion

The offset correction is done in two modes, DC offset correction and more elaborate correction by functional fitting. The DC fitting can be done in a relatively short integration period and the functional fitting can be done by longer integration period. We do show the example in the following.

4.1 DC offset correction

This DC correction is done using the equation (1) as described in chapter 2. The amount of resolution to be corrected is roughly about 50 ppm. Figs.3a and 3b show this example for flat base and flat top of the integrated field and a raw voltage respectively. Clean field signal is observed as expected. Fig.3c shows the example of clear ripple signal when an active filter of the power supply control circuit is turned off. Ripple frequency of 200 Hz is seen in this example.

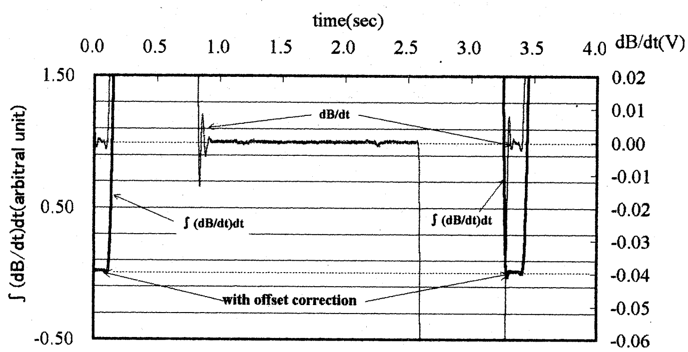

Fig.3a Search coil output voltage and its flux. Flat base portion is magnified.

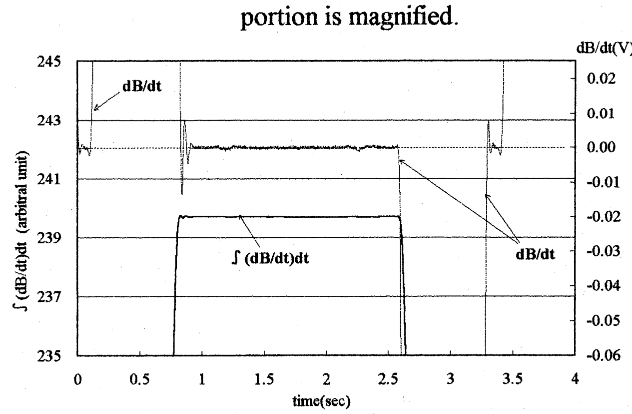

Fig.3b Search coil output voltage and its flux. Flat top portion is magnified.

Fig. 4 shows an example of accurate measurement. This is the case of short DC offset correction of 4 seconds. The fine structure of a field deviation better that 100 ppm is clearly seen. This deviation is reproducible and stable which shows the stability of the measurement method. It is found that there is a coupling between the two main bending magnet power supplies of each synchrotrons by this measurement. Other new findings such as a correlation between this field disturbance and the beam position of the extracted beam. Further study is underway.

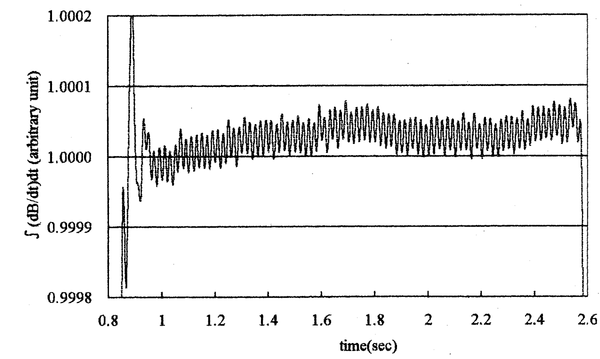

Fig.3c Magnification of 200 Hz ripple at flat top

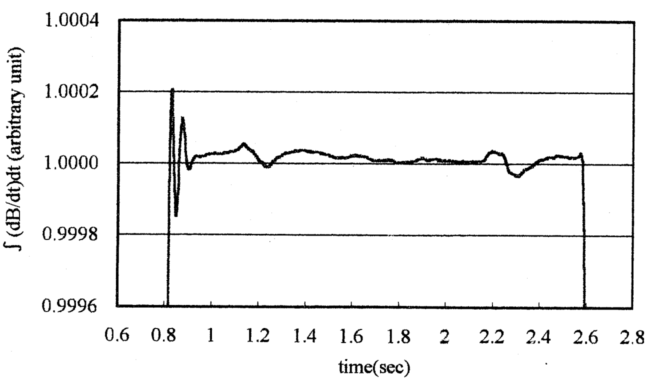

Fig.4 Flux at flat top

4.2 Functional correction

Offset voltage is not necessary to be constant but it may drift. This drift voltage sometimes varies in a sinusoidal way. Fig.5 shows a long drift where an integration is performed for 32 seconds. In the figure, only sequence of flat tops are shown. Long sinusoidal voltage drift is superimposed in this plot. The slow sinusoidal component is fitted using orthogonal sine and cosine function for this case as,

$$\Delta B(t) = a_0 \exp(-b_0 t)\cos(c_0 t + d_0) + e_0 \exp(-f_0 t)\sin(g_0 t + h_0) \qquad (2)$$

where coefficient $a_0, b_0, c_0, d_0, e_0, f_0, g_0$ and h_0 are determined by a least square method. Fig.6 is replotted subtracting the sinusoidal functional correction using the eq.(2). Although, there still remains a residual offset effect, the amplitude of the offset is corrected by roughly factor of 2.

4.3 Optimization of the search coil

FFT analyzer HP35670A has a resolution of 16 bit and a dynamic range better than 90 dB. The effective area of the search coil used in this measurement is chosen to be roughly 1 m^2. The output voltage of the search coil in the bending magnet with a ramping rate of 2 Tesla/sec, which is the maximum rating of this power supply, is about 2 V_{peak}. To improve a SN ratio, this effective area should be increased to the FFT's full scale input voltage, which is 31.7 V_{peak}.
In order to improve frequency response of the measurement, a new fast ADC which is capable of external triggering is being under development. DSP(Digital Signal Processor) is also under development. The final goal is to implement the accurate search coil measurement system in the feedback system of the power supply.

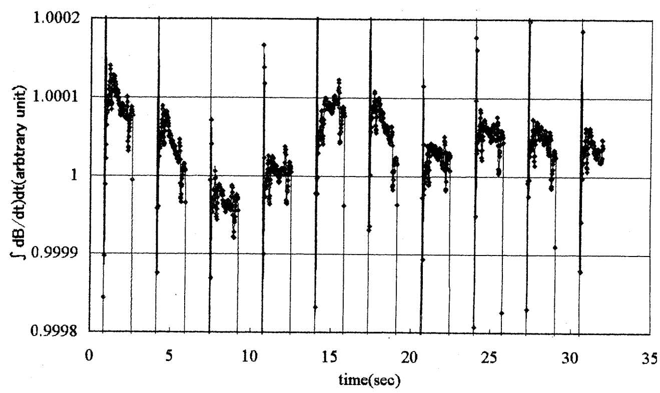

Fig.5 Long time drift of flat top

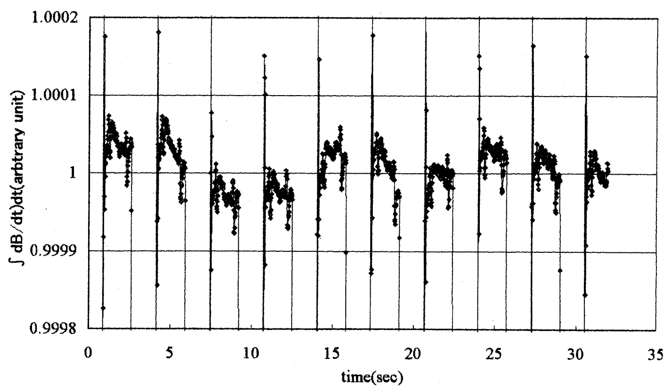

Fig.6 Long time drift of corrected flat top

5 Summary

We have developed an accurate magnetic measurement system using search coil with digital integration device of wide dynamic range. This system leads to a finding of fine structure of the magnetic field at the flat top and the flat base. Those findings include a finding of a coupling between the power supplies and between the magnets in the synchrotron ring and correlation between a fine beam structure in the extracted beam line. This method could be further improved by implementing into the feedback system, which is also under study.

Acknowledgement

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Reference

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