Frequency Response of Slow Beam Extraction Process

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Abstract

A servo control system has been incorporated into the practical slow extraction system in order to stabilize the spill structure less than a few kHz. Frequency responses of the components of the servo-spill control system and the open-loop frequency response were measured. The beam transfer function of the slow extraction process was derived from the measured data and approximated using a simple function. This is utilized to improve the performance of the servo-loop.

I. INTRODUCTION

A slow beam extraction using a half integer resonance has been utilized in the KEK 12 GeV PS [1]. In the slow beam-extraction process, the beam is debunched by turning off the rf, the horizontal tune is shifted close to the half integer resonance by the focussing lattice quadrupole magnets (Q_F's), the extraction quadrupole magnet (EQ) and the octupole magnet are turned on to produce separatrix and then beam is shaven by increasing horizontal tune slowly using Q_F's [2,3]. Ideally the spill of the slow extracted beam is constant in time during extraction period. But in practice the spill structure is raised by the ripple of the magnet power supply and the re-bunching of coasting beam. Servo-spill control system have been used in KEK PS to suppress the spill structure less than a few kHz due to the ripple of the magnet power supply [2]. The improvement of the spill structure is an urgent problem because:
(1) recent renewal of the slow extraction system makes a change in loop dynamics,
(2) the elongation of a slow-extraction period (four times as long as before) deteriorates the spill structure [4],
(3) the spill structure has been imposing restrictions on the data acquisition efficiency of the physics experiments, especially on those experiments utilize the 12 GeV high intensity proton beam or variable-energy primary ion beams.

In order to reduce lower frequency spill structure, two approaches have been pursued. One is to reduce the intrinsic ripples due to thyristor rectifier and to improve the disturbance elimination characteristic of the MR power supply [5]. The other is to improve the performance of the servo-spill control system. The latter approach is investigated in this paper.

To understand and improve the control characteristics of the servo-spill control system, the open-loop frequency response and the frequency response of the elements of the loop were measured. In these measurements, the assumption has been made that the system behaves approximately as a linear system at the small amplitude region. The frequency response of slow beam extraction process is derived from these measured values and was approximated by a simple function. The analysis of the loop dynamics using this result is presented in another session of this Symposium [6].

II. TRANSFER FUNCTION OF THE SPILL CONTROL SYSTEM

In order to stabilize the spill structure, the spill signal measured by secondary emission chamber (SEC) [7] have been fed back to the quadrupoles (the EQ and a ripple quadrupole magnet (RQ)) via servo-spill controller. Schematic diagram of the whole system is shown in Fig. 1 [2].

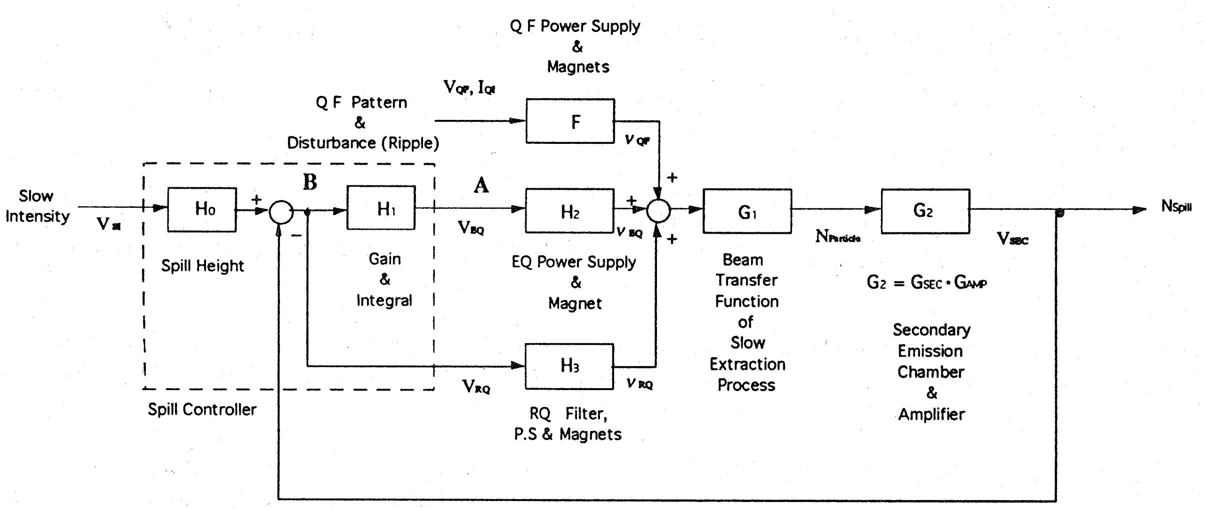

Fig. 1 Schematic diagram of a servo-spill control system

The intensity signal at the beginning of the beam extraction is converted to the DC voltage by a sample-and-hold circuit and is used for the reference of the feedback loop with appropriate gain H_0. The difference signal between the spill signal and the intensity is divided into two signals for the EQ and RQ. The beam is extracted by changing the horizontal tune which is controlled by the Q_F, EQ and RQ. The main disturbance on the system comes from Q_F power supply. The ripple signal can be applied as feed-forward at the point A in Fig.1 with appropriate gain and phase [8]. In order to extract the frequency response of slow beam extraction process, only the loop via EQ is investigated here because of simplicity.

The transfer function of the controller for the EQ is

$$H_1(s) = k_1 \cdot \frac{1 + s\,T_2}{1 + s\,T_1} \cdot \frac{1 + s\,T_3}{s}, \qquad (1)$$

consisting of a phase-lag controller and an integrator, where k_1 is a gain and T_1, T_2 and T_3 are 15.6 ms, 3.72 ms and 0.78 ms, respectively. The integrator is intended to cancel out the differential characteristic of the slow extraction process, i.e.

$$n_{SPILL}(t) = \frac{dv_H}{dt} = k\,\frac{dI_{QF}}{dt} \quad \text{or} \quad N_{SPILL}(s) = k\,I_{QF}\,s.$$

The measured frequency response is shown in Fig. 2.

The measured frequency response of the EQ with a magnet is shown in Fig. 3 [9]. The transfer function is approximated by a second-order low pass filter with an additive phase shifter as

$$F_{EQ}(s) = \frac{\omega_0^2}{s^2 + 2\,\xi_0\,\omega_0\,s + \omega_0^2} \times \frac{-s + \omega_1}{s + \omega_1} \cdot \frac{s^2 - 2\,\xi_2\,\omega_2\,s + \omega_2^2}{s^2 + 2\,\xi_2\,\omega_2\,s + \omega_2^2}, \qquad (2)$$

where $\omega_0 = 2\,\pi$ 3100 rad/sec, $\xi_0 = 0.77$, $\omega_1 = 2\,\pi$ 8500 rad/sec, $\omega_2 = 2\,\pi$ 10000 rad/sec and $\xi_2 = 0.77$. The EQ is a laminated magnet (0.35 mm thick). The transfer function of the laminated core was measured [10] and the frequency response was almost flat at frequencies less than a few 10 kHz in both gain and phase characteristics.

The bellows ducts are used inside the EQ. The measured frequency response of the bellows ducts was also almost flat at frequencies less than 10 kHz in both gain and phase characteristics.

The transfer function of the SEC is considered to be

$$G_{SEC}(s) = \frac{k_4}{s + T_4}, \qquad (3)$$

where k_4 is a gain and $T_4 \approx 45$ µsec, regarding the capacitance of 700 pF of the system and the input impedance of 10 kΩ of the pre-amplifier. The pre-amplifier just after the SEC has the cut off frequency of ~38 kHz.

The only component that is unknown is a slow beam extraction process (beam transfer function). Then the beam transfer function can be derived by subtracting all other frequency responses from the open-loop frequency response.

The open-loop characteristic was measured by two methods. One is to add external sinusoidal signal into the summation point (B) and measure the difference between this signal and the spill signal. The measured quantity is the

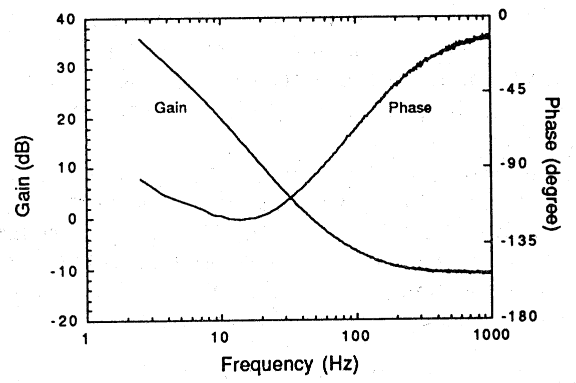

Fig. 2 Frequency Response of the controller for EQ.

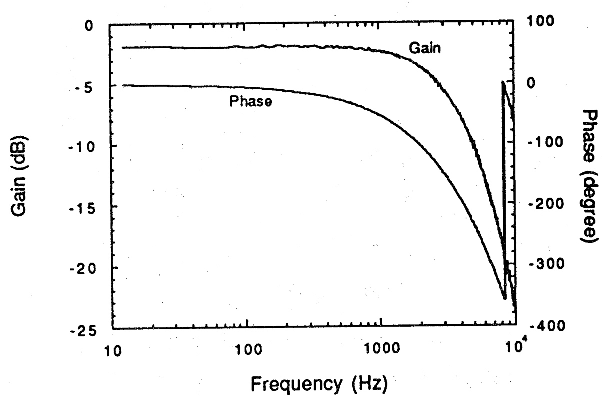

Fig. 3 Frequency Response of the EQ.

closed-loop transfer function in this method:

$$\frac{G_2\,G_1\,H_2\,H_1}{1 + G_2\,G_1\,H_2\,H_1}.$$

The precision tends to be worse in the region where $G_2\,G_1\,H_2\,H_1 >> 1$. The other is to insert the voltage source which is driven by a current probe connected to the signal generator of the servo analyzer. This is inserted at the point C. The measurement points are just after and before the voltage source. The open-loop frequency response can be measured directly by this method [11]. The ADVANTEST 2911C Servo Analyzer was used for both signal generation and measurements. During the measurement the signal level was kept small enough not to destruct the stable beam spill. The effective spill duty factor [12] with and without the external signal were 80 - 92%, 90 - 95%, respectively. The agreement of the two measurements was good in the region, $G_2\,G_1\,H_2\,H_1 \leq 1$. Then the frequency response from 10 Hz to a few kHz was measured by the latter method. The KEK PS has two slow beam extraction lines, EP1 and EP2. The systems are almost same each other[4]. The behavior of the transfer functions was similar for the two cases. The result for the case of EP1 is shown in Fig. 4. The dips at 20, 50, 100, 150 and 200 Hz are due to rather bad coherency of measured signals raised by large amplitude harmonic components of power supply ripple. Figure 4 indicates that the gain margin is about 20dB and phase margin is about 50 degree in this case. The closed-loop is stable. The disturbance, however, cannot be suppressed completely. When the power supply ripple increases a few times as much, spill structure becomes bad. Such phenomena occur due to the external disturbance [13] or lower energy operation. From this point of view the loop dynamics has been investigated [6].

The derived transfer function of the slow extraction process is shown in Fig. 5, subtracting the frequency response of the controller (Eq. (1)) and of the EQ (Eq. (2)) from the measured open-loop response without care for absolute gain. The transfer functions of the other elements are almost constant in this frequency range as described above.

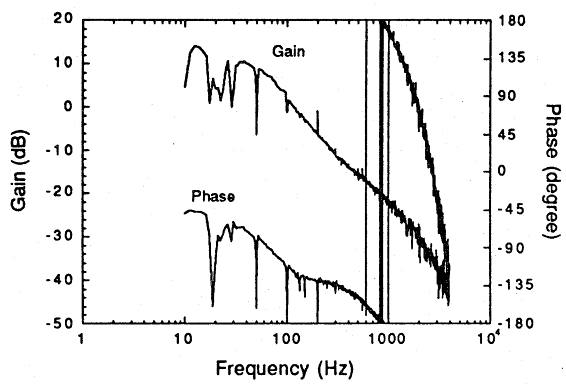

Fig. 4 Open-loop frequency Response of the EP1 servo-spill control system.

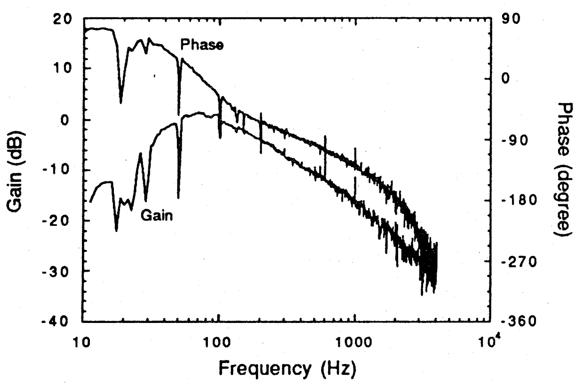

Fig. 5 Transfer function of the slow extraction process.

III. DISCUSSIONS

As supposed the response has differential characteristic in lower frequency region less than ~70 Hz. The gain, however, decreases continuously at frequencies greater than ~70 Hz. The phase lag is very large and exceeds −180 degree at about 2 kHz and seems to increase continuously in higher frequencies.

The transfer function of the slow extraction process is modeled using the measured result. The gain curve seems to be approximated by a second-order band pass filter. The phase curve, however, dose not have the characteristic of a second-order band pass filter. There is a constant phase-lag component. The expected delay time from Fig. 5 is ~800 μsec (~1.3 kHz). This value seems to be very large comparing the simple view of the slow beam extraction process. Each particle in the beam spills out from the separatrix and goes inside the septum area. It takes a few 10 turns, corresponding to the delay time of a few 10 μsec, because the revolution frequency is ~1 MHz at the top energy of the KEK PS .

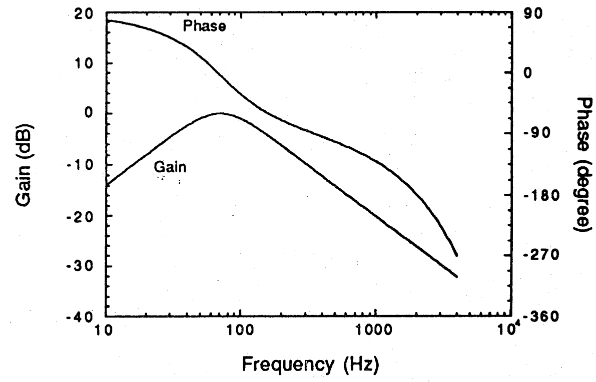

Fig. 6 Transfer function of the slow extraction process.

The approximated transfer function is

$$G_1[s] = \frac{2\,\xi_{BTF}\,\omega_{BTF}\,s}{s^2 + 2\,\xi_{BTF}\,\omega_{BTF}\,s + \omega_{BTF}^2} \cdot e^{-T_{BTF}\,s}, \quad (4)$$

where $\omega_{BTF} = 2\,\pi\,70$ rad/sec, $\xi_{BTF} = 0.7$, $T_{BTF} = 800/(2\,\pi)$ μsec as shown in Fig. 6. It remains for a future study to understand the beam transfer function behavior from the viewpoint of the beam dynamics.

In conclusion the frequency response of the slow beam extraction process was clarified and this results provides a key information to design the servo-spill control system.

IV. ACKNOWLEDGEMENTS

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