THE FIRST STAGE MODIFICATION OF THE SERVO-SPILL FEEDBACK SYSTEM FOR THE SLOW RESONANT BEAM EXTRAXTION FROM THE IHEP 70 GEV PROTON SYNCHROTRON

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Abstract

This paper presents the results of the first stage modification of the servo-spill feedback system for the slow resonant beam extraction from the IHEP 70 GeV proton synchrotron. The system has a time delay caused by resonance evolution. In the past the time delay was estimated equal from 1ms to 1.8ms, and the maximum open loop frequency cut-off was considered equal to a few tens Hz. The servo-spill feedback system was being used with the open loop frequency cut-off no more than 20Hz for many years. The qualitative analysis of the beam motion on the phase plot, the modeling of the system on the base of the Hamilton's equations numerical solution and the analysis of the experimental frequency responses indicated that the time delay value is noticeably less than former estimations. The first stage modification of the servo-spill feedback system has increased the open loop frequency cut-off at the beginning of extraction process up to approximately 300 Hz. The suppression coefficients of the beam intensity ripples are about 2–3.5 at the range 30–200 Hz.

INTRODUCTION

The servo-spill feedback system was being used in the slow extraction from the IHEP 70GeV proton synchrotron with the open loop frequency cut-off no more than 20Hz for many years. The system has a time delay caused by a resonance evolution. The open loop frequency cut-off for a control system with a time delay can be estimated from the following considerations. The stability phase margin is usually chosen equal to 60 degrees. The slope of the open-loop Bode magnitude plot at the frequency cut-off should be equal to 20dB/decade that corresponds to phase displacement 90 degrees. Hence the phase displacement from the time delay at the frequency cut-off is equal to 30 degrees. In the past the time delay was estimated equal from 1ms [1,2]– to 1.8ms [3] and the maximum open loop frequency cut-off of the system was considered equal to a few tens Hz. The value of time delay in [3] was got from the numerical analysis of the beam motion and from the analysis of the experimental frequency responses.

The best result on the bandwidth obtained in the past was described in [4], where two-channel configuration of the tune adjusting system was applied. The quadrupole with the gradient of 2.4T/m (20Q-50-240) was used in the high frequencies channel, but the basic tune adjusting lens 20Q50-1000 with the gradient of 10T/m in the low frequencies channel. The 20Q-50-240 was planned in the project of the extraction systems for the fast resonant extraction and for suppression of the beam intensity ripples in a time of the slow resonant extraction. The open loop frequency cut-off of the low frequencies channel was attained about 16 Hz, and the logarithmic gain-frequency characteristic of the high frequencies channel had a shape of the 12 dB peak at 50Hz. The spill fluctuation suppression coefficient at 50Hz was equal about 3–4. Note should be taken that the open loop phase displacement at 50Hz was equal to 360 degrees. The authors accounted for this phase displacement by the presence of two parallel regulation circuits. It turned out, that the system described in [4] was unreliable and ineffective and so in the practice of the slow extraction in two-channel version was not being used.

RESEARCH OF THE SYSTEM CHARACTERISTICS

The close study of the information on the slow beam extraction detected the following. First of all, the maximum slope of the logarithmic open loop gain-frequency characteristic, where the input value is a voltage on the tune adjusting lens and the output value is the output signal of the beam intensity monitor, was in [4] equal to 20 dB/decade but in [1,3] no less than 40dB/decade. Secondly, the estimation of the time delay by analysis of the frequency responses presented in [3] given the time delay in several times letter than 1.8 ms.

In order to receive the answers on the appearing questions was proposed the model of the tune adjusting system on base of the numerical solution of the beam motion equations [5]. The one-degree of freedom motion without taking into account parasitic non-linearities in magnetic field and momentum spread of the beam was examined. Hamiltonian in the rotating action angle polar coordinates system ($\sqrt{J}, \varphi_1$) is given by

$$H = 2\pi\delta J + \varepsilon J^{3/2}\cos 3\varphi_1,$$

where δ is tuning out resonance value. Fig.1 illustrate essence of the method proposed in [5]. The grid of the smaller stable triangles and radial lines is superimposed on the stable triangle. The areas and the centres of gravity of the elementary trapeziums are calculated. The corresponding to the elementary trapeziums electric charges are assumed proportional to the values of areas. When δ is decreased, the stable triangle sizes are decreased also, and the macro-particles found themselves in the unstable motion domain are moved out along a separatrix in accordance with beam motion equations. The Hamilton's equations of macro-particles motion are solved by Bulirsch-Stoer method. Since the dynamical motion is the canonical transformation, the particles are moved in consecutive order. Therefore the particles by the fixed point adjoining to the outward arm of separatrix come first to the septum. Hence it is clear, that although the motion times of the various particles are different, the time delay in the system is determined only by the time of motion along arm of separatrix from fixed point to the septum.

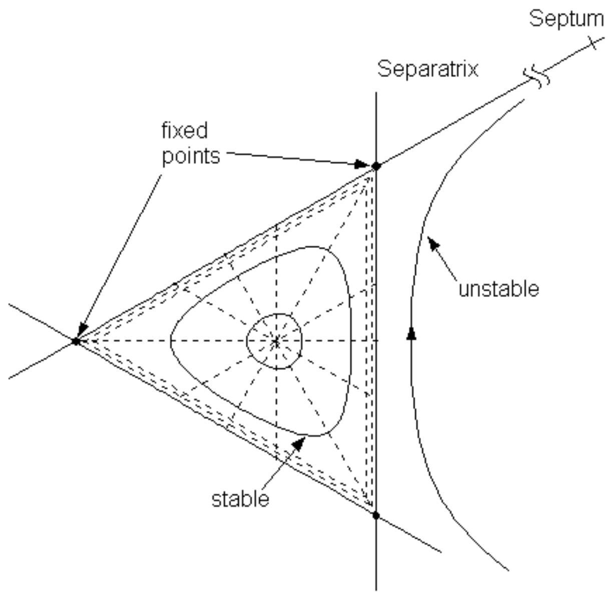

Figure 1: Phase space plot in ($\sqrt{J}, \varphi_1$) coordinates of a third-integer resonance with the lines of grid.

In [3] the time delay was considered equal to a sum of the motion times along arm of separatrix and along side of stable triangle.

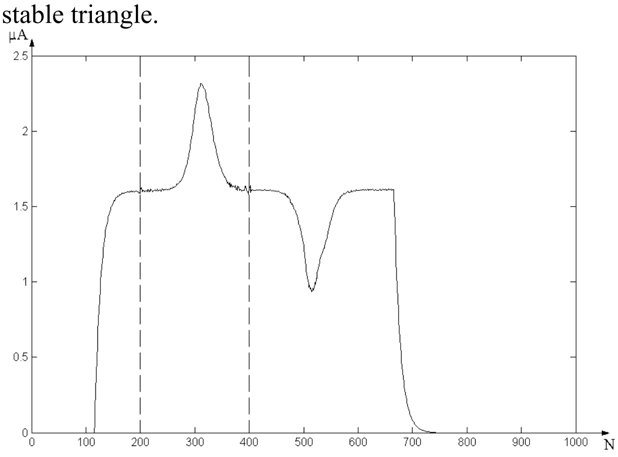

Figure 2: The beam current in the head septum aperture step responses on the jumps of δ at N=200 and N=400.

In Fig. 2 are presented the calculated step responses of the beam current in the aperture of the head septum at the beginning of the extraction process when carry out the linear tune adjustment with the speed equal to δ_{res}/s, where δ_{res}– the stop-band width. The calculations are fulfilled by the method stated in [5]. The parameters of the accelerator and the exciting of sextupoles are taken from [3]. The beam intensity is assumed equal to 10^{13} protons. At the abscissas axis are given a numbers of beam turns. The decreasing of δ is begun at N=0. The negative jump of δ is implemented at N=200 and the positive jump at N=400. The jumps values are equal to $10^{-4}\delta_{res}$. The obtained computation value of the time delay is no more than 0.35ms. The shapes of the responses presented in Fig.2 display that the modelling part of the system is the successive connection of one differentiating and two aperiodic links with the identical time constants. The presence of the aperiodic links in the system is caused by change of the particles motion velocity along the stable triangle side. The velocity is maximum at the middle of the stable triangle side and minimum at the fixed points. The time constant equality of two aperiodic links is caused by the process symmetry with respect to the middle of the stable triangle side.

As regards the finding of the time delay value from the experimental frequency responses the fact is that in [3] was assumed that all phase displacement is connected with the time delay. The phase displacement connected with decrease of amplitude was disregarded.

When the power supply fulfilled as voltage source, the complete system contains no less than three aperiodic links since the coil of the tune adjusting lens is also the aperiodic link. Thus the complete system has the slope no less than of the second order in the high frequency domain with taking into account differentiating link.

For analysis of the frequency response characteristics is used the Levenberg-Marquardt method [6] with the help of which one can get by the existent precision of the frequency responses measuring only a estimations of the system parameters. The frequency response presented in [3] is approximated of the third order model with the time delay about 0.25 ms that corresponds approximately to the maximal open loop frequency cut-off 330 Hz. An origin of the additional aperiodic link besides stated above is not known to date.

DECISIONS ON THE SERVO-SPILL FEEDBACK SYSTEM DESIGN

The introduction in a system of a forcing links for the compensation of aperiodic ones makes great demands to the technical properties of the power supply first of all to the output own pulsation. The available power supply for the lens 20Q50-1000 with the maximum current 1150A answer not the demands of the servo-spill feedback system in respect both the output own pulsation and output voltage diapason, and its modification is a complex problem. Therefore was decided to use two-channel configuration of the system with using of lenses 20Q50-1000 and 20Q50-240. Since the complete system have the slope of no less than second order in the high frequency domain the power supply for the lens 20Q50-240 is fulfilled as the voltage controlled current source. This is allowed to avoid of the including in the system of the aperiodic link caused by the lens coil. It is worked out and made the power supply of uninterrupted type with the push-pull bipolar transistor output cascade and internal current feedback. The maximum output current of the power supply is equal to 50A and the maximum output voltage is equal to 50V. The bandwidth of the power supply is about 3kHz.

EXPERIMENTAL RESULTS

In Fig. 3 are presented the experimental logarithmic open loop frequency responses of the high frequency channel where the input value is a current in the 20Q-50-240 and the output value is the output signal of the beam intensity monitor.

In Fig. 4 are presented the experimental results on suppression of the beam intensity ripples. At the left side in Fig. 4 are presented the signal of beam intensity monitor and its spectrum before switching on the second channel of the system, and at the right side are presented ones after switching on the second channel. One can see substantial improvement of the summary beam intensity signal and the suppression coefficients in the spectrum about 2–3.5 at the range 30-200Hz.

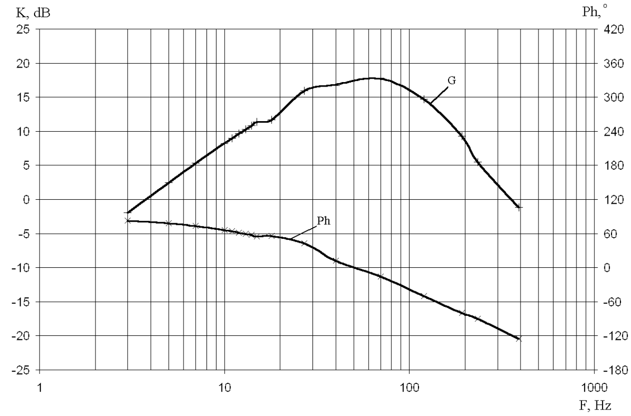

Figure 3: The experimental logarithmic open loop frequency responses of the high frequency channel. G –gain, Ph – phase.

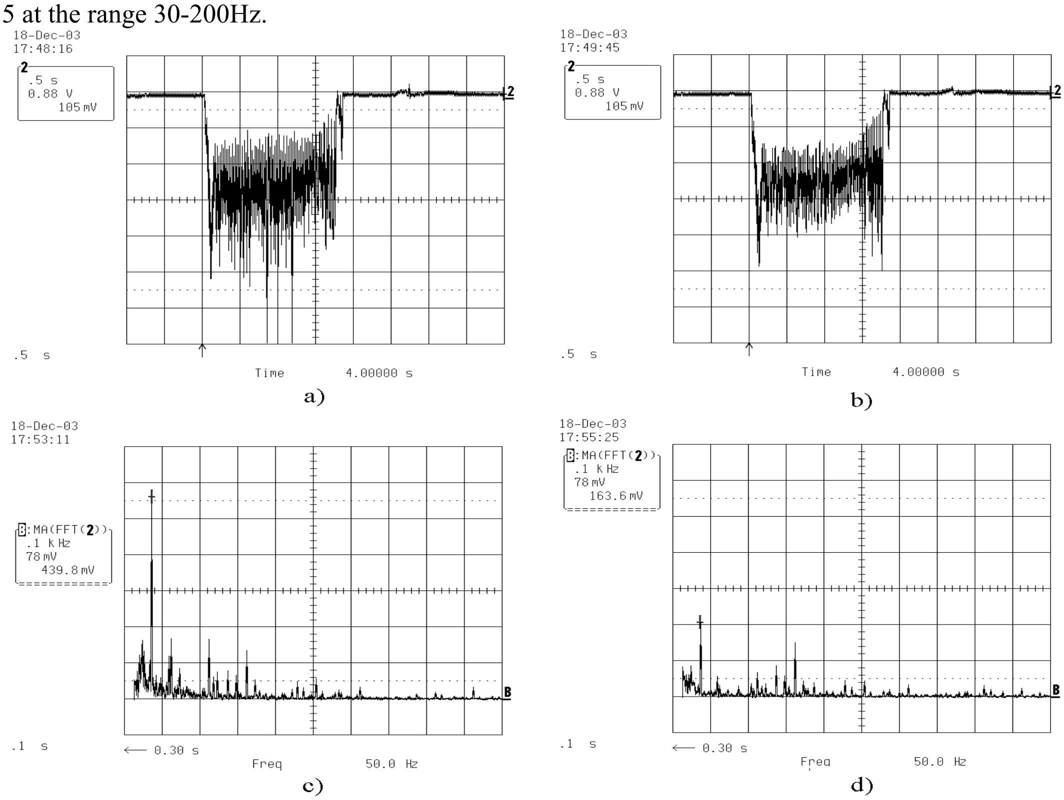

Figure 4: a), the signal of beam intensity monitor and c) its spectrum before switching on the second channel of the system, b), d), these same after switching on the second channel.

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