PHASE TROMBONE PROGRAM MIGRATION FOR THE RECYCLER RING AT FERMILAB*

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Abstract

A best matching algorithm was found using a test program written in Mathematica, and was integrated into an accelerator control on-line program. This on-line program now gets rid of network communication, and does not need to run code MAD. In this report, we first describe the matching conditions, and 4 cases of constrains. Using a test program written in Mathematic, given a change of tunes, we were able to find the possible combination of the quadrupole strength in trombone section for each case. We then tested the calculation results by simulations using code MAD and by experiments on the Recycler ring. Finally we found the best matching algorithm and integrated it into an accelerator control on-line program. The test results for the setting and measured tune values by running on-line program on console are also presented.

INTRODUCTION

In the Recycler Ring, a phase trombone is used to control tunes. Instead of distributing remotely adjustable quadrupoles around the ring, 9 pairs of independently power supplied adjustable quadrupoles are located in RR-60 straight section [1]. They are segmented into 5 families currently to maintain a symmetrical structure. By adjusting these circuits, a tune variation of up to ±0.5 units is attainable. These adjustments are coordinated in such a way that the Twiss parameters at the ends of the straight section keep unchanged.

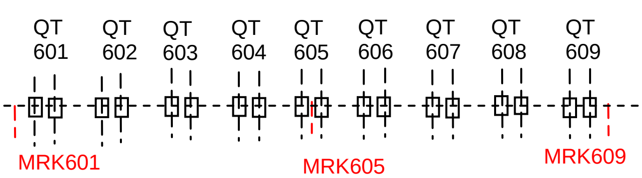

Figure 1: Phase trombone RR-60 straight section

To accomplish the tune adjustment in operation, a console application program, which was supposed for temporary use, but has been used for years since Recycler ring commissioning, sent the request through internet to another computer (Bonson), and run MAD[1] there to look for best combination of quadrupole strengths in 5 families by match the request, then send the results through the internet again back to the console. It results in long response time, even the program can not work if the internet service is broken down. Actually the computer Bonson was running only for this purpose. On the other hand, the matching algorithm was not proper, the solution given by MAD was often away from the expected tune changes. Our issue here is to get rid of network communication and trying not to use MAD anymore.

MATCHING CONDITIONS

Each of 9 quadrupoles in RR-60 straight section has their own power supply. In principle, each of them can be adjusted independently as long as keeping the conditions that the Twiss parameters at the two ends of the straight section unchanged.

We know the changes of the tunes in x and y planes are as follows:

$$\Delta\nu_{x,y} = \pm\frac{1}{4\pi}\sum_i \int_0^L \beta_{x,y}(s_i)k(s_i)ds_i \qquad (1)$$

$k(s_i)$ is the strength of i^{th} quadrupole, $\beta_{x,y}(s_i)$ is the beta-function of the quadrupole. On the other hand, we have

$$\begin{pmatrix}\beta 2\\ \alpha 2\\ \gamma 2\end{pmatrix} = \begin{pmatrix} M_{11}^2 & -2M_{11}M_{12} & M_{12}^2 \\ -M_{11}M_{21} & M_{11}M_{22}+M_{12}M_{21} & -M_{12}M_{22} \\ M_{21}^2 & -2M_{21}M_{22} & M_{22}^2 \end{pmatrix}\begin{pmatrix}\beta 1\\ \alpha 1\\ \gamma 1\end{pmatrix} \qquad (2)$$

For both x and y planes. where M_{11},M_{12}, M_{21} and M_{22} are the elements of the transfer matrix M of the straight section, which are also the functions of the quadrupole strengths. We know γ is a function of α and β, we actually only get two independent equations in each plane. Totally, we get 6 independent equations.

To calculate the transfer matrix M of the straight section, first we output transfer matrices from MAD between two trim quads, and take each quad as thin element, with integrated strength $(kL)\rightarrow 10^{-3}$, as follows:

$$M_q = \begin{bmatrix} \cos(\sqrt{k_x}L) & \frac{1}{\sqrt{k_x}}\sin(\sqrt{k_x}L) & 0 & 0 & 0 & 0 \\ -\sqrt{k_x}\sin(\sqrt{k_x}L) & \cos(\sqrt{k_x}L) & 0 & 0 & 0 & 0 \\ 0 & 0 & \cosh(\sqrt{k_x}L) & \frac{1}{\sqrt{k_x}}\sinh(\sqrt{k_x}L) & 0 & 0 \\ 0 & 0 & \sqrt{k_x}\sinh(\sqrt{k_x}L) & \cosh(\sqrt{k_x}L) & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & \frac{L}{\beta_s^2\gamma_s^2} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\approx 0 \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ -kL & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & kL & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

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and then concatenate the transfer matrix for whole section

$$\mathbf{M} = \mathbf{M}_{\mathbf{d20}} \cdot \mathbf{M}_{\mathbf{q609}} \cdot \mathbf{M}_{\mathbf{d19}} \cdot \mathbf{M}_{\mathbf{q609}} \cdot \mathbf{M}_{\mathbf{d18}} \cdots \mathbf{M}_{\mathbf{q601}} \cdot \mathbf{M}_{\mathbf{d2}} \cdot \mathbf{M}_{\mathbf{q601}} \cdot \mathbf{M}_{\mathbf{d1}} \qquad \mathbf{(5)}$$

where $\mathbf{M}_{d1}$, $\mathbf{M}_{d2}$, … $\mathbf{M}_{d20}$ are the matrices of drift space between two quads, $\mathbf{M}_{q601}$, $\mathbf{M}q_{602}$, … $\mathbf{M}_{q609}$ are the matrices of the quads 601, 602 to 609. Note that each quadrupole is split into two pieces in the machine.

TEST PROGRAM IN MATHEMATICA

A test program was written in Mathematica. The transfer matrix for whole section is first concatenated in the program as given in Equation (5), and then the equations are linearized so that only first order terms of i^{th} quadrupole strength k_i are kept. It turns out to be a least-squares problem, which can be solved by SVD (Singular Value Decomposition). There are four cases for the conditions of matching and constrains, listed as follows. Note that K in the following equations represents the integrated strength of the quadrupole,

$$K = kL = 0.00297 /(m \cdot Amp) \times L \times I$$

where is circuit current, L is the length, L=0.3048m.

Case 1

Match half section and keep symmetrical structure start at MRK601, meaning that 9 quadrupoles are segmented into 5 families to maintain a symmetrical structure. Given $\Delta\nu_x$ and $\Delta\nu_y$, and constrain $\alpha_{x,y}$ =0 at MRK605. Then we obtain

$$\begin{pmatrix} \mathbf{20.2866} & \mathbf{21.7847} & \mathbf{-16.7561} & \mathbf{4.0436} & \mathbf{10.0463} \\ \mathbf{-89.36} & \mathbf{-4.0040} & \mathbf{95.9540} & \mathbf{1.8302} & \mathbf{-46.6866} \\ \mathbf{3.2579} & \mathbf{16.1036} & \mathbf{2.6351} & \mathbf{14.6924} & \mathbf{3.46450} \\ \mathbf{-14.9367} & \mathbf{-2.6092} & \mathbf{-15.7204} & \mathbf{-3.1664} & \mathbf{-14.3777} \end{pmatrix} \begin{pmatrix} K_1 \\ K_2 \\ K_3 \\ K_4 \\ K_5 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ \Delta\nu_x \\ \Delta\nu_y \end{pmatrix}$$

In this case, we have only 4 independent equations, but 5 variables, fewer equations than unknowns, the solutions are not unique.

Case 2:

Match full section, but keep symmetrical structure start at MRK601. Given $\Delta\nu_x$ and $\Delta\nu_y$, and constrain $\alpha_{x,y}$ and $\beta_{x,y}$ at MRK609. Then we obtain

$$\begin{pmatrix} \mathbf{-46.3705} & \mathbf{-36.5735} & \mathbf{73.6231} & \mathbf{31.819} & \mathbf{-34.1699} \\ \mathbf{40.3347} & \mathbf{44.4282} & \mathbf{-32.6486} & \mathbf{9.4943} & \mathbf{19.9027} \\ \mathbf{2651.77} & \mathbf{146.482} & \mathbf{-2622.23} & \mathbf{-22.8425} & \mathbf{1435.44} \\ \mathbf{-167.604} & \mathbf{-7.2958} & \mathbf{183.006} & \mathbf{3.7388} & \mathbf{-87.5826} \\ \mathbf{3.2344} & \mathbf{15.7290} & \mathbf{2.6319} & \mathbf{15.0529} & \mathbf{1.7325} \\ \mathbf{-14.8699} & \mathbf{-2.6608} & \mathbf{-15.712} & \mathbf{-3.1073} & \mathbf{-7.1889} \end{pmatrix} \begin{pmatrix} K_1 \\ K_2 \\ K_3 \\ K_4 \\ K_5 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \Delta\nu_x \\ \Delta\nu_y \end{pmatrix}$$

In this case, we have 6 independent equations, but 5 variables, more equations than unknowns. This is an overdetermined set of linear equations. We found that the singular values are :(4008.92, 57.66, 43.32, 20.44, 3.94), the ratio of maximum to the minimum of the singular value is in the order of 10^3, means that it is in ill condition.

Case 3:

Match full section, but release two quads in one of the 5 segmented families, for example QT604 and QT606, to be independently adjustable. Given $\Delta\nu_x$ and $\Delta\nu_y$, and constrain $\alpha_{x,y}$ and $\beta_{x,y}$ at MRK609.

$$\begin{aligned} K_1 &= -3.2961\times10^{-7} + 0.0303\Delta\nu_x - 0.1392\Delta\nu_y \\ K_2 &= -7.4378\times10^{-9} - 0.0199\Delta\nu_x + 0.0124\Delta\nu_y \\ K_3 &= \ \ 1.3359\times10^{-8} - 0.0099\Delta\nu_x - 0.0281\Delta\nu_y \\ K_4 &= -2.8449\times10^{-8} + 0.0930\Delta\nu_x - 0.0036\Delta\nu_y \\ K_5 &= \ \ 6.5553\times10^{-7} - 0.0727\Delta\nu_x + 0.20644\Delta\nu_y \\ K_6 &= \ \ 2.8708\times10^{-8} + 0.0888\Delta\nu_x - 0.0002\Delta\nu_y \end{aligned}$$

Case 4:

Match full section, and keep symmetrical structure start at MRK601. Given $\Delta\nu_x$ and $\Delta\nu_y$, and only constrain $\alpha_{x,y}$ =0, but leave $\beta_{x,y}$ at MRK609 for observation. Then we obtain

$$\begin{pmatrix} \mathbf{40.3347} & \mathbf{44.4282} & \mathbf{-32.6486} & \mathbf{9.4943} & \mathbf{19.9027} \\ \mathbf{-167.6040} & \mathbf{-7.2958} & \mathbf{183.0060} & \mathbf{3.7388} & \mathbf{-87.5826} \\ \mathbf{3.2344} & \mathbf{15.7290} & \mathbf{2.6319} & \mathbf{15.0529} & \mathbf{1.7325} \\ \mathbf{-14.8699} & \mathbf{-2.6608} & \mathbf{-15.7120} & \mathbf{-3.1073} & \mathbf{-7.1889} \end{pmatrix} \begin{pmatrix} K_1 \\ K_2 \\ K_3 \\ K_4 \\ K_5 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ \Delta\nu_x \\ \Delta\nu_y \end{pmatrix}$$

Again, we have only 4 independent equations, but 5 variables. Although the solutions are not unique, we found that the singular values are (269.369, 48.782, 21.606, 9.878). The ratio of maximum to the minimum of the singular value is about 27, means that it is in good condition.

TESTING RESULTS

For a given change of tunes $\Delta\nu_x$ and $\Delta\nu_y$, SVD solution provides the possible combination of the quadrupole strength in trombone section. Putting the quadrupole strengths calculated from the TROMBONE program in Mathematica for Case 1, 2 and 3, we have run code MAD and later run Recycler machine to verify the expected tune changes, the results are listed in Table 1. dQ_x and dQ_y are expected tune change, $d\nu_x$ and $d\nu_y$ are simulated or measured values. We see that the deviations of the tune changes from both MAD calculation and measurement in the machine in Case 2 and case 3 are large, but small in Case 1. However, we noticed that the beta-function changes in x and y planes at MRK609 are large, up to 20% in Case 1.

It was found that Case 4 works exactly as we want. Therefore, we decided to put this algorithm into the module of an accelerator control on-line program. The module is written in C, using SVD standard function from Numerical recipes [2], named TROMBONE.

Table 1 Simulated and experimental results for Case 1, 2 and 3

(dQ_x, dQ_y) (expected)		*($\Delta\nu_x$, $\Delta\nu_y$) (simulated by MAD)*	*($\Delta\nu_x$, $\Delta\nu_y$) (measured in Recycler)*
(0.002, 0.002)	case1	0.0019,0.0020	0.0020,0.0013
	case2	0.0019,0.0020	-0.0034,0.0017
	case3	0.0020,0.0020	0.002,0.0017
(0.005, 0.005)	case1	0.0055,0.0046	0.0051,0.0051
	case2	0.0046,0.0051	0.0037,0.0047
	case3	0.0050,0.0049	0.0186,0.0192
(0.01, 0.01)	case1	0.0109,0.0093	0.0101,0.0095
	case2	0.0091,0.0103	0.0085,0.0095
	case3	0.0098,0.0099	
(0.02, 0.02)	case1	0.0221,0.0186	0.0216,0.0186
	case2	0.0179,0.0212	0.0172,0.0199
	case3	0.0195,0.0200	
(0.02, -0.02)	case1	-0.0206,0.0157	0.0243,-0.0196
	case2	0.0083,-0.0110	0.0135,-0.0172
	case3	0.0235,-0.0015	
(-0.02, 0.02)	case1	0.0203,-0.0159	-0.0189,0.0132
	case2	-0.0083,-0.0110	0.0071,-0.0223
	case3	-0.0200,0.0223	
(-0.02, -0.02)	case1	-0.0221,-0.0184	-0.0223,-0.0189
	case2	-0.0198,-0.0207	-0.0206,-0.0206
	case3	-0.0212,-0.0200	

On-line program TROMBONE was installed and tested for the tune changes in Recycler machine. First of all, we set the currents of all 9 trim quadrupoles in Trombone section to 0, and adjust the skew quads in the Recycler to split the tune further, the base tunes measured in *x* and *y* planes are (0.423, 0.413) and the tune split is 0.01 (noted that this is the minimum tune split we can get at this time of the machine conditions). Then we set the requested tune changes in TROMBONE program, and measured the tunes in Recycler. We found that the program runs smoothly, the deviations of the measured tune changes (the settings) from the requested (the readings) are less than 0.003 if the two tunes are setting apart, see Table 2. If we set the two tunes together, the deviation is about 0.006, which is listed in the last row of Table 2. Note that the beta-functions at the end of the trombone section in both *x* and *y* planes can always be kept within 3%.

Conclusion

Phase Trombone Program in the Recycler has been successfully migrated. This program now gets rid of network communication, and does not need to run code MAD. For safety reason, the currents of trim quadrupoles are set the limitation to 6.5 Amps. In this case, the largest tune change in horizontal plan would be limited to 0.06, but 0.18 in vertical plan. The TROMBONE program is now running well for the operation.

Table 2 Experimental results for Case 4.

(dQx, dQy) (expected)	*(Δvx, Δvy) (Measured)*	*(Δvx, Δvy) (simulated by MAD)*	*($\Delta\beta/\beta$)x, ,($\Delta\beta/\beta$)x, (%) at MRK609*
0.004, -0.068	0.001, -0.062	0.004, -0.068	0.57, 1.33
0.01, -0.012	0.007, -0.009	0.01, -0.012	0.04,0.11
0.08, -0.08	Beam lost	0.08, -0.08	3.07,1.63
0, 0.1 (Half integer)	Beam lost	0, 0.1	-0.65, -1.95
0.02, 0	0.018,0.003	0.02, 0	0.64,0.02
0.01, 0	0.009,0.002	0.01, 0	0.32,0.009
-0.01, 0 (coupled)	-0.017, -0.006	-0.01, 0	-0.32, -0.009

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[2] W.H.Press, etc al, “ Numerical Recipes in C: The Art of Scientific Computing”. Second Edition, (section 2.6 and 15.4). Cambridge University Press, 1992.

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