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AN OPTIMIZATION METHOD OF THE NOSE-CONE BUNCHER CAVITY

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Abstract

The nose-cone buncher cavity is widely used on proton accelerators. It's important to properly optimize the cavity geometry for fine RF performance. However, currently the optimization is usually carried out manually and the criteria are not objective enough. In this paper, an optimization method using the multi-objective, multi-variable optimization approach is presented. The geometry and RF parameters are considered as the variables and objectives respectively. The goal function is defined as the weighted sum of multiple RF parameters. The multi-variable functions are approximately derived from the single-variable functions based on electromagnetic simulation. And an optimization code is developed accordingly which has been applied to the XiPAF debuncher optimization.

INTRODUCTION

The Xi'an proton application facility (XiPAF) is a synchrotron proton accelerator built for radiation effects research. There's a debuncher on the medium energy transport line (MEBT) to reduce the beam energy spread. The nose-cone buncher cavity is adopted, which has been widely used on proton accelerators as bunchers or debunchers [1, 2]. Since the RF performance depends on the cavity geometry, the optimization of the cavity geometry is a vital procedure of debuncher design. The optimization aims for optimized RF performance like low probability of RF breakdown and high shunt impedance and Q factor while keeps the resonance frequency exactly equal to the RF frequency, which is 325 MHz in the case of XiPAF.

A lot of optimization work of nose-cone buncher cavities has been carried out, in which, the manual way that determining the geometry parameters by evaluating their effects on the RF parameters based on electromagnetic (EM) simulation is adopted accordantly [1-4]. However, since multiple RF parameters should be optimized synchronously while their values are decided by multiple geometry parameters, the criteria of the manual optimization approach are not objective enough and the results mostly rely on experience. Therefore, a common optimization method which could automatically accomplish the nose-cone buncher cavity optimization under specific demands is in need.

An optimization method using the multi-objective, multi-variable optimization approach is presented in this paper. By treating geometry parameters and RF parameters as the variables and objectives respectively, the optimized cavity geometry would be obtained mathematically via optimization algorithm.

APPROXIMATE FUNCTION

Relation Between RF and Geometry Parameters

The function between variables and objectives are the footstone of multi-objective, multi-variable optimization. The RF and geometry parameters considered as the variables, objectives and constraint in the optimization are shown in Table 1. Three geometry parameters that affect the cavity geometry most intensely are adopted as the optimization variables primarily.

Using EM simulation software CST a parametric model of the nose-cone cavity is established as shown in Fig. 1, based on which the relation between the RF and geometry parameters is studied by parameter sweep. The effective cavity voltage VT is 160 kV and the beam energy E_{beam} is 7 MeV while calculating the bravery factor b and the transient time factor T.

Applying polynomial fit to the simulation data, one-dimensional approximate functions between RF and geometry parameters are acquired.

Table 1: Variables, Objectives and Constraint

roles	parameters	symbol
objective	effective shunt impedance	R
	Q factor	Q
	bravery factor	b
variable	cavity radius	r
	gap length	g
	nose cone angle	t
constraint	resonance frequency	f

Approximate Function between RF and Geometry Parameters

The multidimensional functions that contain all variables for each objective are in need to accomplish the optimization. It can be approximately derived from the one dimension functions acquired via EM simulation.

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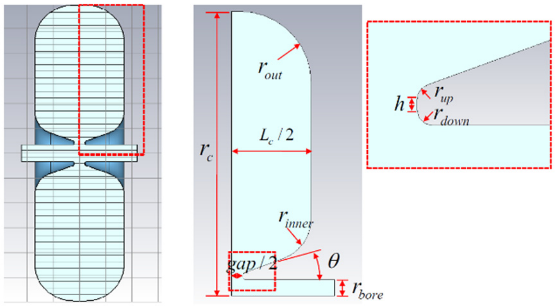

Figure 1: The parametric EM model of the nose-cone cavity.

Assuming that the wanted approximate functions of RF parameters are in the form of polynomial as follows:

$$F(x,y,z) = F_1(x) + F_2(y) + F_3(z) + A \tag{1}$$

where A is an unknown constant and F_j is a one-dimensional polynomial function:

$$F_j(t) = \sum_{i=1}^{n} p_{ji} t^i \quad t = x, y, z; \quad j = 1,2,3; \quad n = 1,2,...... \tag{2}$$

where p_{ji} is the polynomial coefficient. According to the EM simulation result, F as one-dimensional functions near the anchor point of the 3-dimensional domain (x_0, y_0, z_0) are acquired. Then F_j can be derived from the following equations:

$$F(x,y,z)|_{y=y_0, z=z_0} = F_1(x) + A_1 \tag{3}$$

$$F(x,y,z)|_{z=z_0, x=x_0} = F_2(y) + A_2 \tag{4}$$

$$F(x,y,z)|_{x=x_0, y=y_0} = F_3(z) + A_3 \tag{5}$$

where A_1, A_2, A_3 are unknown constants. Name the value of $F(x, y, z)$ at (x_0, y_0, z_0) as F_0.

$$F_0 = F(x_0, y_0, z_0) = F_1(x_0) + F_2(y_0) + F_3(z_0) + A \tag{6}$$

Then $F(x, y, z)$ can be expressed with F_0 and F_j.

$$\begin{aligned} F(x,y,z) &= F_0 + (F - F_0) \\ &= F_0 + [F_1(x) - F_1(x_0)] + [F_2(y) - F_2(y_0)] + [F_3(z) - F_3(z_0)] \\ &= \sum_{i=1}^{n} p_{1i}(x^i - x_0{}^i) + \sum_{i=1}^{n} p_{2i}(y^i - y_0{}^i) + \sum_{i=1}^{n} p_{3i}(z^i - z_0{}^i) + F_0 \end{aligned} \tag{7}$$

By this means the approximate function of the objectives can be expressed as follows:

$$Q(r,g,t) = \sum_{i=1}^{n} p_{ri}(r^i - r_0{}^i) + \sum_{i=1}^{n} p_{gi}(g^i - g_0{}^i) + \sum_{i=1}^{n} p_{ti}(t^i - t_0{}^i) + Q_0 \tag{8}$$

$$R(r,g,t) = \sum_{i=1}^{n} p_{ri}(r^i - r_0{}^i) + \sum_{i=1}^{n} p_{gi}(g^i - g_0{}^i) + \sum_{i=1}^{n} p_{ti}(t^i - t_0{}^i) + R_0 \tag{9}$$

$$E(r,g,t) = \sum_{i=1}^{n} p_{ri}(r^i - r_0{}^i) + \sum_{i=1}^{n} p_{gi}(g^i - g_0{}^i) + \sum_{i=1}^{n} p_{ti}(t^i - t_0{}^i) + E_0 \tag{10}$$

as well as the approximate constraint function:

$$f(r,g,t) = \sum_{i=1}^{n} p_{ri}(r^i - r_0{}^i) + \sum_{i=1}^{n} p_{gi}(g^i - g_0{}^i) + \sum_{i=1}^{n} p_{ti}(t^i - t_0{}^i) + f_0 \tag{11}$$

The range of parameters are shown in Table 2 which covers the existing application of buncher cavities reported [1-4]. In order to get fine accuracy the whole range is separated into three parts and the frequency at three anchor points are 310 MHz, 330 MHz, 350 MHz.

Table 2: Range of Parameters

parameters	range	anchor point
f / MHz	300~360	310,330,350
g / mm	10~25	17.5
t / °	10~45	27.5
r / mm	236.9~313.8	298.9，271.6，247.6

OPTIMIZATION ALGORITHM

Goal Function

To solve the optimization mathematically a goal function is in need firstly. Knowing the aim of optimization is to get larger Q and R as well as lower b, the goal function is defined as the weighted sum of those RF parameters where the weight of b is minus. Then considering the approximate functions of the RF and geometry parameters the goal function can be expressed as

$$P(g,t,r) = k_Q Q(g,t,r) + k_R R(g,t,r) - k_b b(g,t,r) \tag{12}$$

Where k_F is the weight value of each objective, initially set as 1. Note that Q, R, b are parameters with different dimensions. In order to add them up the non-dimensional values are adopted as shown in Table 3. The bigger the P is, the more the corresponding result is preferred under the given weight values.

Table 3: Units for the Non-Dimensional Values

objectives	unit
Q	10^4
R	MΩ
b	1

For the expected RF frequency f_{RF}, the constraint condition is as follows:

$$f(g,t,r) = f_{RF} \tag{13}$$

Optimization Code

An optimization code is developed with MATLAB accordingly. It could automatically output a set of optimized geometry parameters g, t, r corresponding to the given frequency and weights. The run time of the code is only a few seconds since the calculation is as complex as the second order polynomial. The algorithm of the code is as follows:

- Set the optimization conditions including f_{RF} and weights k_Q, k_R, k_b.
- Sweep the variables g, t while calculate the corresponding r using the constraint condition. The step widths are Δg =0.5 mm, Δt =2.5 ° . The ranges of g, t are shown in Table 2.

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- Calculate the goal function *P* with current variables at each step.
- Select the optimized variables g_{best}, t_{best}, r_{best} corresponding to the biggest *P, i.e., P_{best}* as the optimization solution.

Figure 2 is the flow chart of the optimization code.

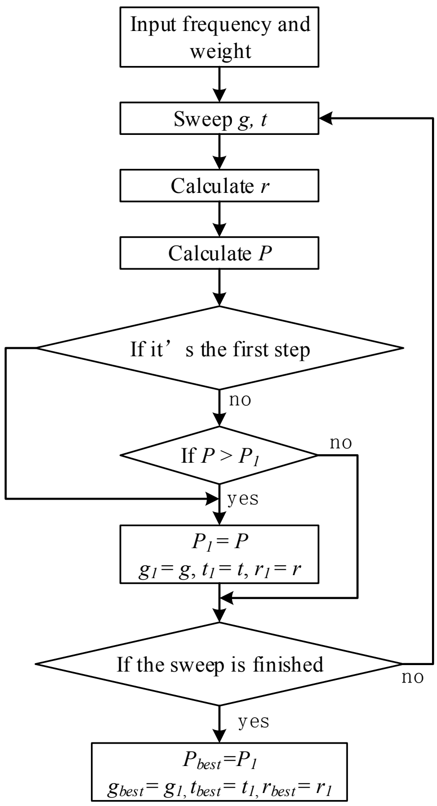

Figure 2: The flow chart of the code.

Performance of Optimization Code

Test the performance of optimization code by comparing the optimization results with the anchor point where *f* is 330 MHz. Calculate the corresponding RF parameters by CST and the results and conditions are shown in Table 4.

Table 4: Conditions and Results of the Test Run

parameters		initial	optimized
constraint	f / MHz	330.0	329.8
objectives	Q	28486	30065
	R / MΩ	3.69	3.81
	b	1.13	0.99
variables	r / mm	271.6	299.5
	g / mm	17.5	25
	t / °	27.5	10
conditions	VT/ kV	160	160
	E_{beam} / MeV	7	7
	f_{RF} / MHz	330	330
	k_Q, k_R, k_b	-	1

It's obvious that all the RF parameters are optimized while the constraint is satisfied within the accuracy of 1 MHz.

OPTIMIZATION OF THE XIPAF DEBUNCHER

Utilize the code to optimize the XiPAF debuncher cavity. In the initial run all the weights are set as 1 while Q and b are optimized compared to the original design that accomplished by manual optimization approach. In order to get better R, adjust the weights in the following run. When kQ, kR, kb are set as 4, 4, 1 respectively, all three RF parameters are optimized as shown in Table 5. The eventual optimized result (optimized 2 in Table 5) is adopted for the XiPAF debuncher manufacture.

Table 5: Optimization of the XiPAF Debuncher

parameters		original	optimized 1	optimized 2
constraint	f / MHz	324.9	324.8	325.7
objectives	Q	27155	30166	28973
	R / MΩ	3.86	3.84	4.09
	b	1.32	0.99	1.11
variables	r / mm	261.2	305.5	291.1
	g / mm	13	25	20
	t / °	20	10	10
conditions	VT / kV	160	160	160
	E_{beam} / MeV	7	7	7
	f_{RF} / MHz	325	325	325
	k_Q	-	1	4
	k_R	-	1	4
	k_b	-	1	1

CONCLUSION

By applying the multi-objective, multi-variable approach to the nose-cone cavity optimization, the optimization code could output the optimized geometry parameters corresponding to the given weights and frequency. It would be a sufficient supplement to the manual optimization work. The optimization result of the XiPAF debuncher via the code has been adopted for manufacture. Currently only three of the geometry parameters are considered as variables while all of them affect the RF performance of the cavity. Besides the suitable beam energy for utilizing the code is 7 MeV only. These should be improved in the further work.

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