Gantry optimization of the Shanghai Advanced Proton Therapy facility*

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(Received March 2, 2015; accepted in revised form May 14, 2015; published online August 11, 2015)

A proton therapy system is a large medical device to treat tumors. Its gantry is of large structure and high precision. A new half-gantry was designed in the Shanghai Advanced Proton Therapy (SAPT) project. In this paper, the weight of gantry in design is reduced significantly by size and structure optimizations, to improve its cost-effectiveness, while guaranteeing the functions and precision. The processes of physics optimization, empirical design optimization, topological optimization and size optimization, together with factors of consideration, are described. The gantry weight is reduced by 30%, with the same precision.

Keywords: Proton therapy, Gantry, Structure optimization, Topological optimization, Size optimization

DOI: 10.13538/j.1001-8042/nst.26.040201

I. INTRODUCTION

A proton therapy (PT) facility is a new-type of large medical device. It mainly consists of injector, accelerator, gantry and therapy system [1–3]. The gantry is used to let a tumor be exposed to proton beams from different angles, so as to reduce significantly injuries to normal tissues. It is of enormous structure and high positioning accuracy [4], with a turning radius of 5–6 m, weight of 100–200 ton, and pointing accuracy of $<$ 1 mm [5–8]. Generally, a PT system is equipped with several gantries. The tendency of gantry design is weight- and volume-reduction under premised precision [9, 10]. The methods include optimization of physical layout, empirical design and mechanical structure. The optimization of physical layout is to reduce overall length and radius of lattice as much as possible by adjusting physical parameters without affecting functions [11]. The optimization of empirical design is based on comprehensive considerations of materials, manufacturing processing technologies, installation, maintenance etc., to reduce structure mass by appropriate choices.

Optimization of mechanical structure means reasonable considerations on structural machinability and safety, while pursuing optimized layout of structure with reasonable size and weight, and guaranteeing its functions and structural strength. This includes optimizations on the gantry topology, shape and size [12]. The topological and shape optimizations are aimed at figuring out desirable shape of the parts in design, and how to arrange the rib plates [13, 14]. Common softwares, such as Hyperworks-optistruct module, are based on FEM calculation of structural model. The calculation is conducted in iteration by modifying FEM mesh, towards a shape feature which meets the constraint conditions. The size optimization focuses on choosing appropriate dimension of parts (such as thickness of plating and length), towards a structure size with reduced weight and ensured structural strength [15–17]. The softwares (e.g. Isight and Optimus) calculate finite sample points by calling FEA program, to find out the relationship between dimension variables and results, and find out optimal allocation plan of design variables which meet design requirements through optimization algorithm (e.g., gradient method and genetic algorithm) [18].

* Supported by the Shanghai Advanced Proton Therapy project (No. Y331061061)
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II. STRUCTURE AND PURPOSE

The Shanghai Advanced Proton Therapy (SAPT) facility, to be built at RuiJin hospital, includes two fix beam and one gantry researched by Shanghai Institute of Applied Physics. Figure 1 shows the half-gantry schematically. The structure consists of stationary and rotating parts, and the latter includes mainly cross and cant beams, transmission beam line, shaft, counter weight, and D and C beams, while front-end bearing seat constitutes the stationary part.

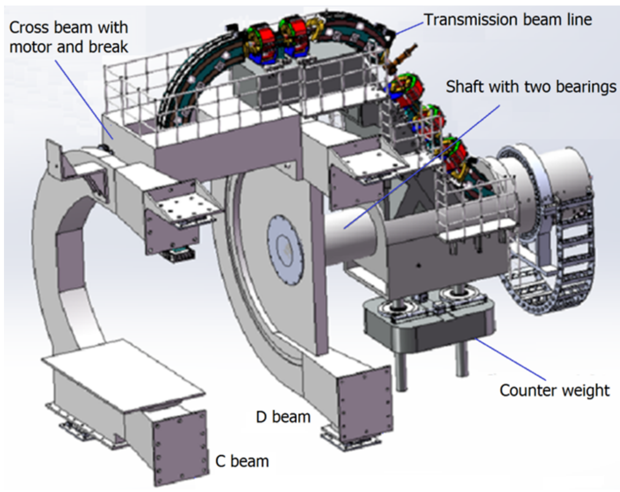

Fig. 1. (Color online) Gantry diagram of SAPT project.

Its design requirement is that the weight of rotating part is below 100 000 kg, and the overall weight is the average level of international products of the same kind. The whole structure is 10.2 m in length and 5.4 m in turning radius. Having a rotary counterbalance with a counter weight, and driven by the servo motor on the cross beam, the gantry can be rotated in 180° and stopped for treatment at any angle. The required precision of crossing point of rotation axis and the nozzle axis shall be within ±0.5 mm. Its main design parameters are given in Table 1.

TABLE 1. Specifications of SAPT half-gantry

Isocentre level	1.3 m above the floor
Overall dimensions	10.8–10.2 m length
Angle of rotation	0°–180°
Isocentre displacement	< ±0.5 mm
turning speed	0.1–1 rpm (adjustable)
Rotation steps	0.05°
Reproducibility	0.2°
Overrun on	0.15° @0.1 rpm
emergency stop	3.25° @1 rpm
AC servomotors	With speed reducer
Breaks	Pneumatic breaks
Rotating weight	< 100 000 kg

The gantry function and precision were of priority in its scheme design, and weight was not considered as a major factor. Table 2 lists main parts and weight of the scheme design. Its structural weight is 240 t, well exceeding those of the IBA (120 000 kg), Michubishi (160 000 kg), Hitachi (190 000 t) and PSI (II, 210 000 kg) gantries [4–7]. Therefore, it is time to reduce its weight by multiple optimization methods while guaranteeing its functions and precision.

TABLE 2. Weight (in kg) of gantry parts before optimization

Rotating parts ($\times 10^3$)		Stationary parts ($\times 10^3$)	
Transmission line	26.4	C beam	32
Main rotating shaft	17	D beam	55
Cant beam	10	Transmission system	26
Cross beam component	15.8	Connecting beam	7
Connecting rod	3.5	Front-end bearing seat	5.1
Connection of counter weight	8	Total	120
Counter weight	34.2		
Total	120		

III. METHODS

A. Optimization procedure

The gantry size shall meet requirements of physics layout and nozzle, its turning radius and length shall be limited. Therefore, to optimize the physics layout and adjust magnet parameters are key tasks in the size reduction, while keeping the functions and parameters. The materials, structure type, manufacturing process and installation method can be chosen after optimized empirical design. Also, the weight-reduced design shall guarantee accuracy requirement of the structure, topological optimization and size optimization of structure. Thus, the optimization was done in the following sequence: (1) physics optimization; (2) empirical optimization; (3) structural static analysis; (4) topological optimization; (5) size optimization; and (6) update structure and verification.

B. Physics optimization

Physics layout of the half-gantry is shown in Fig. 2.

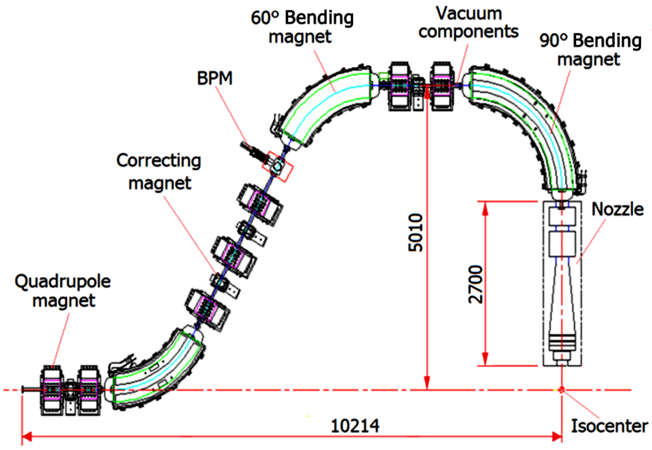

Fig. 2. (Color online) Lattice layout of half-gantry.

Principles of the physics optimization are as follows:

(1) Under the conditions of keeping horizontal and vertical phase shift of the parameters such as beta, alpha and chromatic dispersion in exit and entrance as integral multiples of π, the less the engineering size the better [5, 19].

(2) A stronger field intensity of bending magnet, and a smaller bending radius and external radius of rotating gantry, lead to shorter longitudinal length. Also, the stronger the magnetic field of quadrupole magnet is, and the higher the field intensity is, the smaller the volume of magnet will be Ref. [20].

(3) Longitudinal length of the rotating gantry can be shorted by increasing the rise angle, hence a reduction of the gantry weight, but weight increase of the bending magnet.

(4) Source-to-axis distance (SAD) affects the turning radius, but a too-small SAD affects the treatment effects. SADs of most gantries worldwide are about 3 m [11, 15]. To shorten SAD at PSI, the scanning magnet is placed in front of bending magnet, but this causes other problems [6]. If SAD can be shortened, the weight and volume of gantry will be reduced significantly.

Table 3 shows that the weight of transmission line was remarkably reduced by optimizing lattice and increasing field intensity of bending magnet.

TABLE 3. Optimization results of lattice optimization

Optimized factor	Reduced weight (kg)
Reduce radius of 90° magnet by 191 mm	550
Reduce radius of 60° magnet by 191 mm	$410 \times 2 = 820$
Reduce magnet spacing by 200 mm	1000
Reduce overall length by 320 mm	600
Sum of transmission line:	2970
Counter weight	2370
Total reduced weight	5340

C. Empirical optimization

Optimization of empirical design mainly focuses on:

(1) Reasonable rigidity: In its early design, some components were chosen conservatively. A reasonable structural rigidity means to quit unnecessary components based on experience and remove materials bearing small load.

(2) Appropriate structural mode: some gantry functions can be realized by multiple methods, e.g., installation mode of front-end bearing could be hollow, which is beneficial to transit and installation of transmission line, and a mounting position for bearing seat could be reserved exclusively. Tonnage of the counter weight, either fixed or adjustable, is affected by its adjusting method and the distance of moment arm. Weight and cost could be reduced significantly by choosing reasonable structural type.

(3) Reasonable function selection: The gantry weight is affected by its selective functions, such as a flexible cable tray, cooling mode of magnet, and a maintenance line.

(4) Materials selection: For critical shafts and gearing parts, better materials and heat treatment processes are required, while most unessential parts are made of steel for cost-effectiveness reasons.

(5) Reasonable assembling and adjusting method: The design is affected by the gantry assembling, which is a complex process and needs a mass of tooling structures. The choice of adjusting method affects size and structure of the adjusting plate, and the magnet support.

(6) Selection of manufacturing process: A welded part is better than a cast part in terms of weight reduction and the cost. However, attentions shall be paid against welding deformation problems.

After above analyses for every component, the weight of main parts was reduced significantly (Table 4).

TABLE 4. Weight reduction (in kg) by optimizing empirical design

Components	Original ($\times 10^3$)	Optimized ($\times 10^3$)
Stationary parts		
C beam	32	21
D beam	55	41.6
Transmission system	26	15.2
Connecting beam (cancelled)	7	0
Rotating parts		
Cross beam component	15.8	11.3
Complex of rotating main shaft	17	15.1
Cant beam	10	8.1
Sum	240	185

D. Statics analysis

A change in size of the structure affects its rigidity and rotating precision of the isocenter. Statics finite element analysis should be performed on the optimized structure at different rotating angles, so as to find out load-bearing, deformation and stress conditions of all components. In FEA analysis, complicated fine structures and redundant bolts were removed, and complex parts such as bearings were simplified appropriately. These were done with deviations of less than 1% in overall weight and center of gravity. Surfaces contacting with buildings were fixed, and surfaces contacting of rotating parts, such as locations of bearing gears were set contact couplings. Maximum deformation, stress state and equivalent stress level of main parts, were calculated, and stress concentration in a structure part was modified in detail.

E. Topological optimization

Structures of most rotating gantries are welding parts, of which the rigidity is reinforced by rib plates. However, some rib plates are not necessary. Objective of topological optimization is to remove unnecessary rib plates, the rigidity could be guaranteed, and complexity and cost of structure could be reduced significantly.

According to results of the statics calculation, with the static deformation and stress level being optimization constraints, topological optimization was conducted under different working conditions by the Hyperworks-Optistruct software. Superfluous structures were removed after overall consideration of the results in different conditions, and part designs were updated by adding structures at key positions. Static verification of the parts was conducted finally according to mechanical characteristics of contact surfaces. Considering workload and schedule requirements of optimization, major parts of the cross, cant and D beams were analyzed topologically. Figure 3 shows the topological optimization process of rib plates of the cross parts. Layout density of rib plates on cross beams after optimization was improved, with a weight reduction of about 1200 kg.

F. Size optimization

The size optimization was performed as follows: 1) According to results of statics calculation, every component was offered with constraints of deformation and stress level; 2) Optimus optimization calculation was conducted by loading under different conditions; 3) Optimization results under different working conditions were obtained; and 4) After proper analysis, the structure size was changed. Finally,

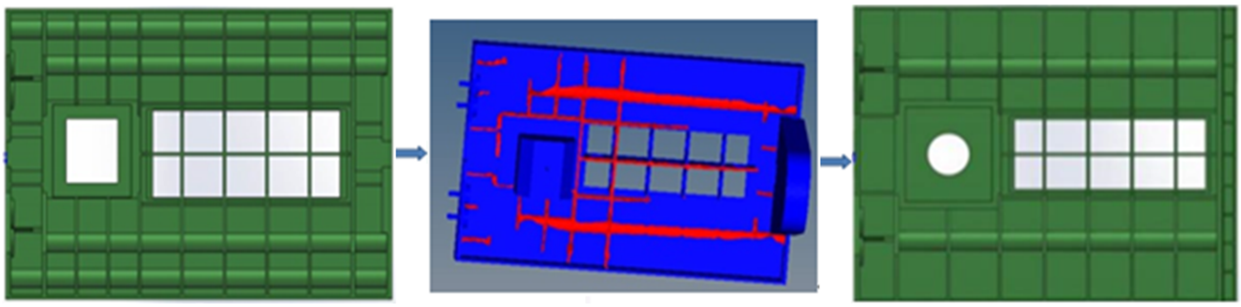

Fig. 3. (Color online) Topological optimization of cross beam component.

static verification was conducted for the optimized structure with confirmed deformation and stress level.

With a view to workload and schedule requirements of optimization, size optimization was conducted mainly for major parts including the cross, cant and D beams. Take the D beam as example, its size parameters, design constraints and objective are shown in Fig. 4, with its design constraints as maximum displacement being ≤ 0.3 mm and maximum stress ≤ 80 MPa, and the design objective of minimum total weight (initial weight) of 41 600 kg. To match the response surface, 30 sample points were selected in Solidworks, Ansys and Optimus. Through the iterating genetic algorithm and gradient method, 28 800 kg was obtained as the optimal weight of D beam, which meets the requirements.

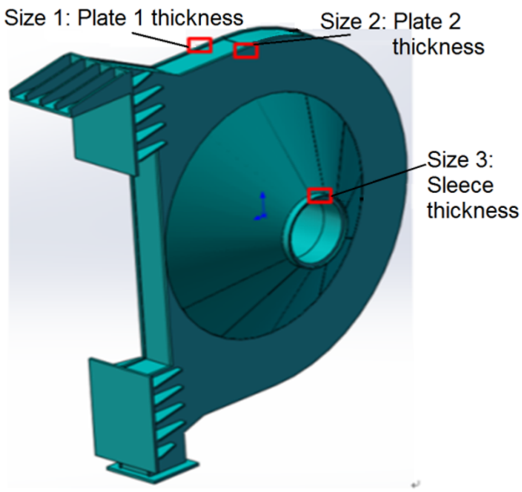

Fig. 4. (Color online) Structure and size variables of D beam.

IV. RESULTS AND VERIFICATION

After optimization, structure size and shape of every component of the gantry meet the design requirement both in its static deformation and strength. By overall considerations on the technology, standardization and structure safety, certain flexibilities in size and structure of the component were adopted. Table 5 lists weight changes of the major parts in every phase of the optimization.

TABLE 5. Weight changes of the major parts ($\times 10^3$ kg)

Parts	Original	P.O. & E.O.[a]	T.O. & S.O.[b]
C beam	32	21	14.3
D beam	55	41.6	28.8
Cross beam	15.8	7.7	6.3
Cant beam	10	9.2	8.3
Transmission line	26.4	21.1	–
Total weight	240	185	162

[a] Physics and empirical optimizations;
[b] Topological and size optimizations.

A modified component design was verified with the overall gantry structure by static analysis, to see whether it met the requirements or not. For major parts of the C, D, cross and cant beams, the maximum deformations of overall structure are 0.04, 0.3, 0.43 and 0.67 mm, respectively, and the equivalent stress values are 9.64, 29.4, 85 and 85 MPa, respectively, all meeting the design objectives and maximum stress level.

V. CONCLUSION

By comprehensive considerations on physics layout, requirements of structure function and precision, technology and safety, optimization techniques are applied to reduce the gantry weight by about 30%, improving significantly the cost-effectiveness. The major safety factor was chosen in the design stage. This is not the final optimization of the gantry, further optimization shall be done after it is manufactured and tested.

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