Optimal Design of Computed Tomography Scanner Structure

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ABSTRACT

Recently, in order to save the cost and to reduce the space for medical electronic equipments, it has become important problem to minimize the weight of the structure, subject to various constraints in operation and manufacturing.

We have studied the feasibility weight reduction for the computed tomography (CT) scanner. In order to obtain the optimal values of many design parameters effectively, the sensitivity analysis capability in MSC/NASTRAN (V65A) and mathematical programming technique (SUMT) were combined. As a result, 25 percent weight reduction was attained.

This paper shows the effectiveness of the present approach for practical size problems.

INTRODUCTION

The X-ray computed tomography scanner is a medical electronic equipment which takes a tomogram of the human body. The key technology is the combination of the X-ray fluoroscope and image processing. The outside aspect is shown in Figure 1, and the schematic structure is shown in Figure 2.

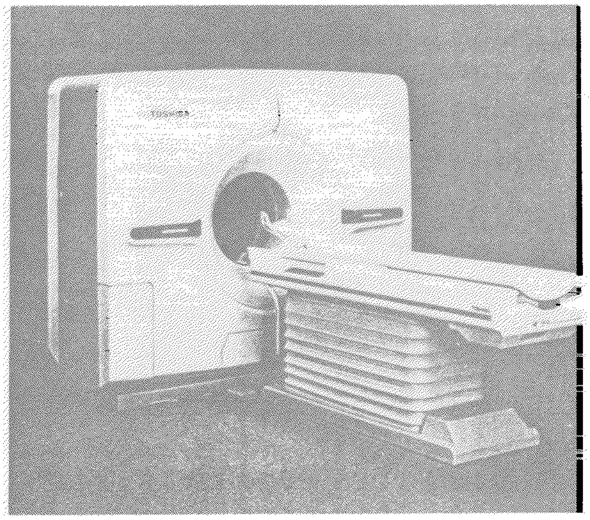

Fig. 1 Outside aspect of CT scanner

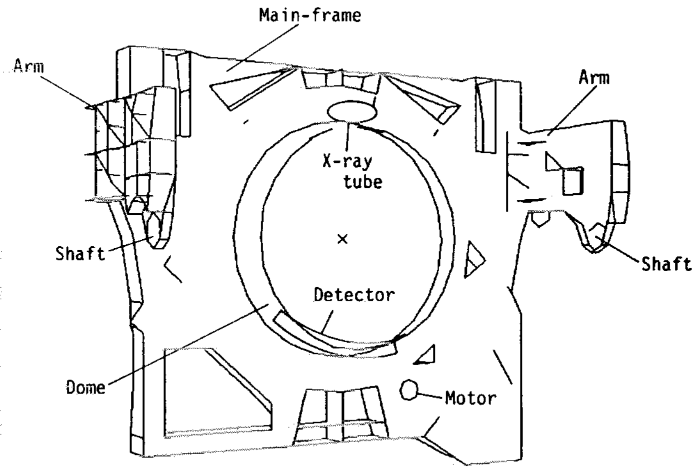

Fig. 2 Schematic structure

The typical mechanism of the CT scanner is that the X-ray tube and the detector which are sited on opposite sides are gathering the projection data with rotating around the human body, and generating the tomogram by image processing.

This time, in order to save the cost and to reduce the space for the CT scanner structure, the problem to minimize the weight of structure subject to various constraints in operation and manufacturing was studied. The approach to that problem and results are reported in the following sections.

DESIGN OPTIMIZATION

APPROACH [1]

By iterating the procedure as shown in Figure 3, the weight minimization of structure was achieved.

(a) Structural Analysis/Sensitivity Analysis [2]

The capability of static analysis and sensitivity analysis in MSC/NASTRAN (V65A) on CRAY-XMP was utilized.

(b) Interface between Sensitivity Analysis and Optimizer [3],[4]

The formulation of the optimization problem is the minimization of an object function subject to equality and inequality constraints.

Minimize W(x)

Subject to

$$
\begin{aligned}
&g_j(x) \leq 0 && j=1, \ldots, m \qquad (1)\\
&h_k(x) = 0 && k=1, \ldots, \ell\\
&x_{\ell i} < x_i < x_{ui} && i=1, \ldots, n
\end{aligned}
$$

where x denotes a vector of design variables, $x=(x_1, \ldots, x_n)^T$.

In this procedure, as shown in Equation (2), inequality constraints were approximated by a Taylor series expansion with constraints and sensitivity matrix which were obtained from MSC/NASTRAN. The object function was defined by using the MSC/NASTRAN property and material table data blocks.

$$g_i(x) = g_i(x^0) + \sum_{j=1}^{n} \frac{\partial g_i}{\partial x_j} (x_j - x_j^0) \qquad (2)$$

where x^0 denotes original design variables.

(c) Optimization [5]

The optimization algorithm was a combination of SUMT using exterior penalty functions and DFP variable metric method. This module was processed on ACOS Computer Systems.

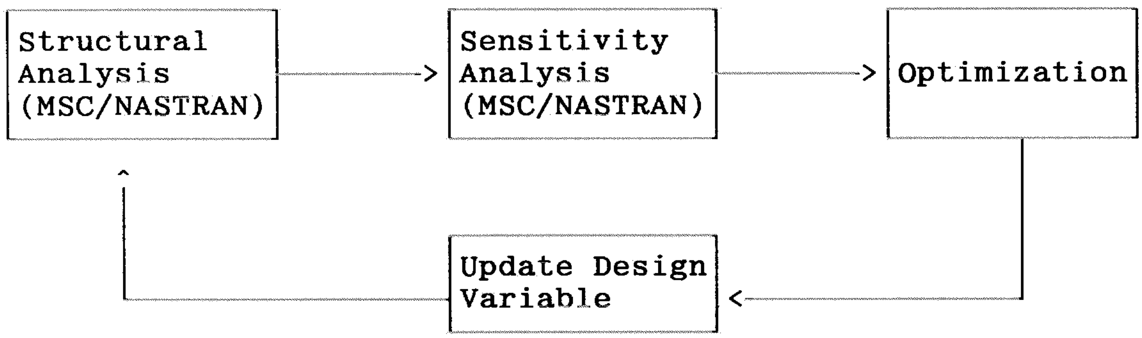

Fig. 3 Procedure of Design Optimization

ANALYSIS MODEL

Main-frame, arms, motor, and rotating part which consists of X-ray tube, detector and others of the CT scanner structure were the object of the structural analysis. Main-frame and arms were modeled using 626 QUAD4s and 245 TRIA3s. The motor was modeled as a concentrated mass. The total number of grid points was 703.

The most interesting structural response controls the quality of the CT scanner image. This response is the displacement at the center of the dome in the main-frame. In order to estimate the displacement, a dummy membrane was utilized, whose stiffness and mass were nearly zero. The FEM model of structure is shown in Figure 4.

The rotating part was modeled as a static moment loading which occurred by rotating the unbalanced mass. The direction of moment was selected that maximizes the displacement at the center of the dome. As another loading condition, the weight of the structure was considered.

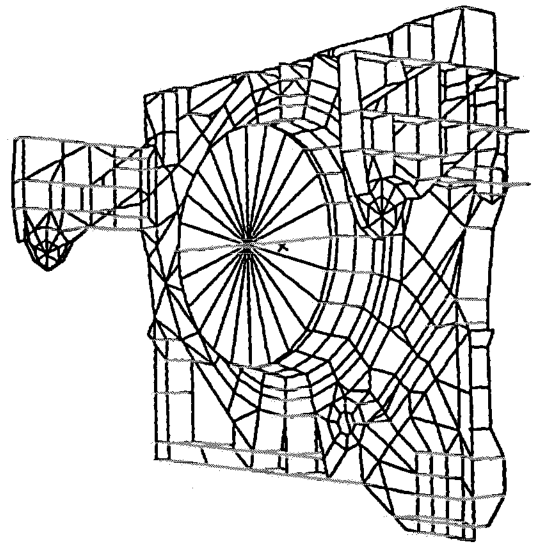

Fig. 4 FEM model

The boundary conditions were spepcified as shown in Figure 5. For the connection between arms and the shaft, all components except the rotating component around the axis of shaft were constrainted. For the arm, the vertical translation component was constrainted.

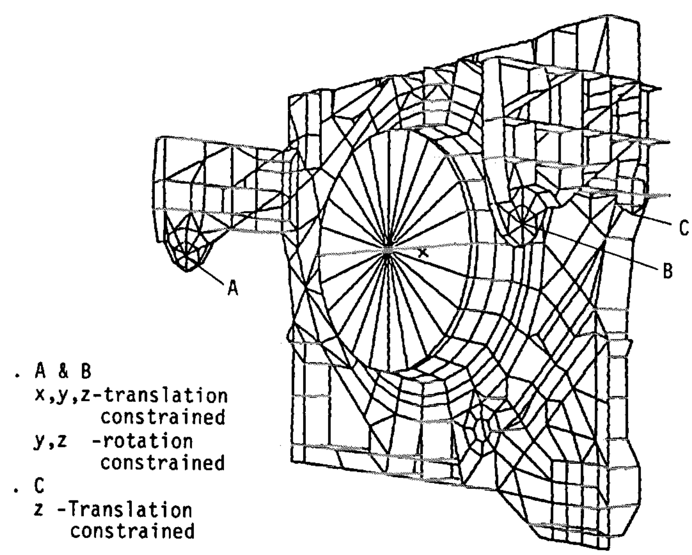

Fig. 5 Boundary Conditions

PROBLEM STATEMENT

The problem is to minimize the weight of the CT scanner structure, within allowable structural response and subject to manufacturing constraints. This problem was formulated to the following structural size optimization problem.

(a) Objective function

The weight of CT scanner structure

(b) Constraints

One of constraints was that the displacement at the center of drum should not exceed the given allowable displacement. The others was the upper and lower limit value of the plate thickness required in manufacturing.

(c) Design variables

This structure is made of plates. The structure is divided into 48 plate thickness groups. 8 plate thickness groups were fixed because of constraints in manufacturing. Therefore, the design variables were set 40 plate thickness groups. The typical design variables are shown in Figure 6.

RESULT

OPTIMAL DESIGN

After the procedures shown in Figure 3 were iterated 8 times, the weight iteration history was given in Figure 7. The weight was reduced 25 percent in the optimal design.

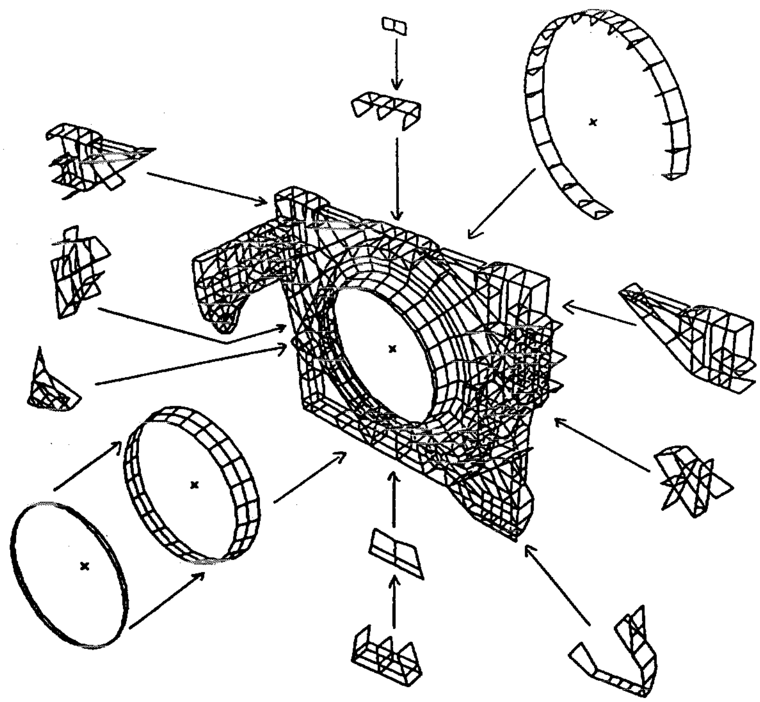

Fig. 6 Typical design variables

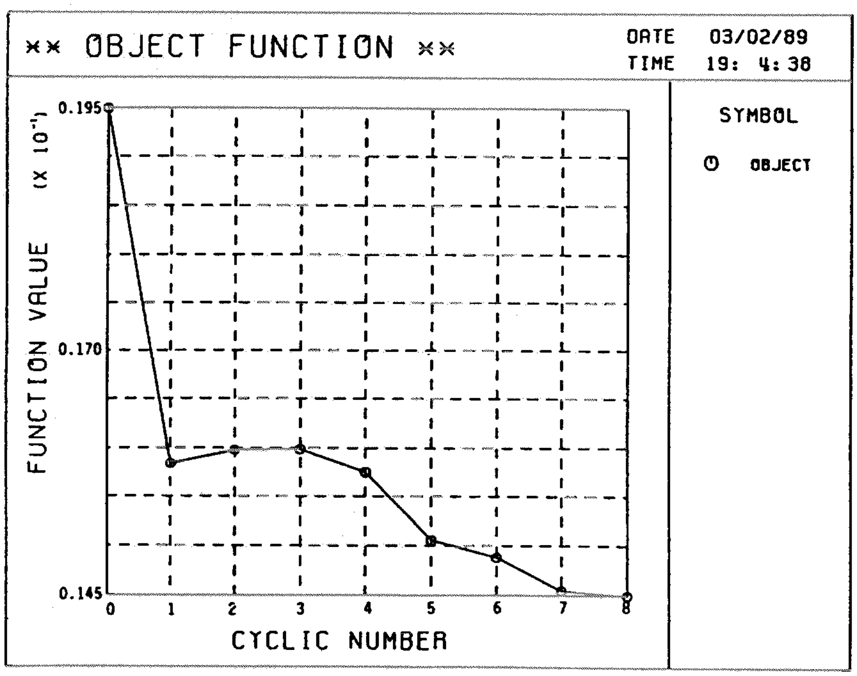

Fig. 7 Weight iteration history

The typical modification of plate thickness are summarized in Figure 8. In this Figure, the modification was divided into three groups specified symbols. It was known that the reduction of weight is realized by not only thinning thickness, but also combining with thickening.

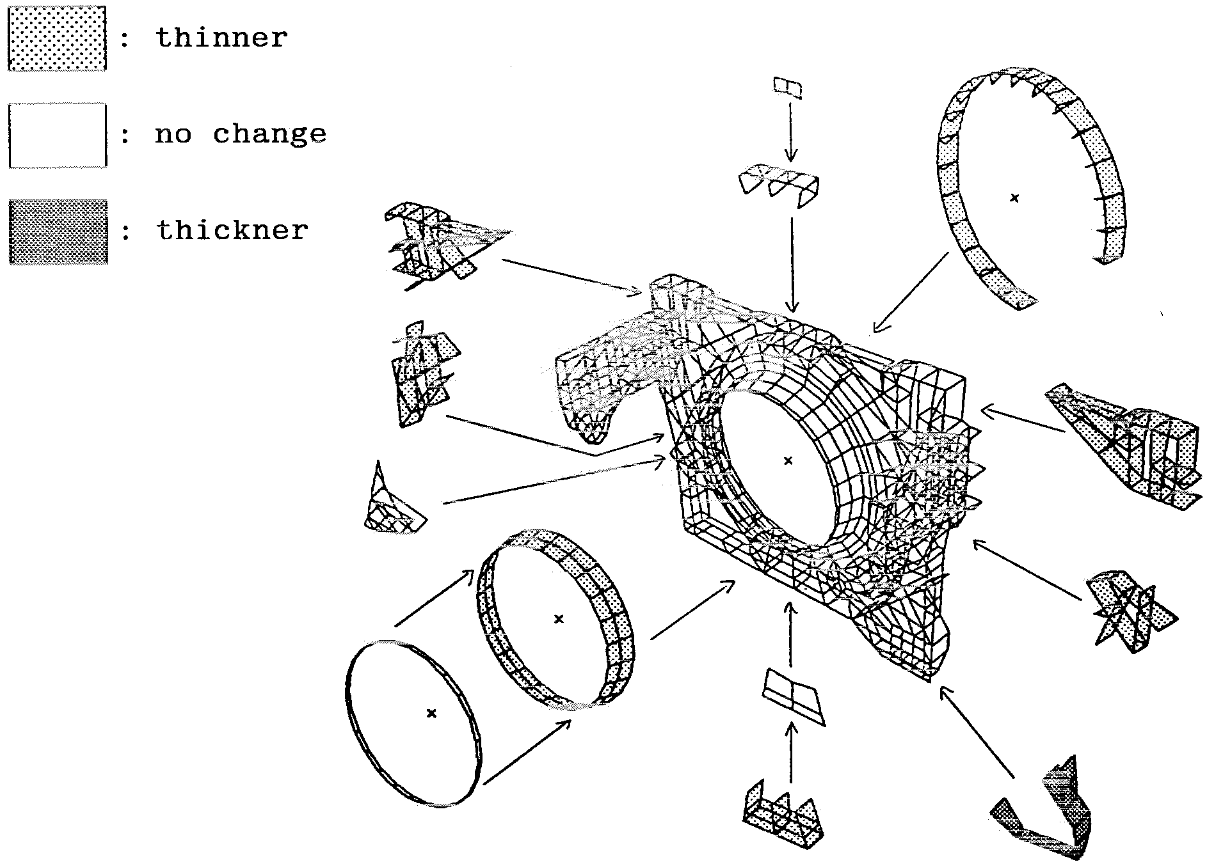

Fig. 8 Typical modification of plate thickness

The constraint history for the displacement at the center of dome is shown in Fig. 9. This Figure presents that the constraints are satisfied in the final design.

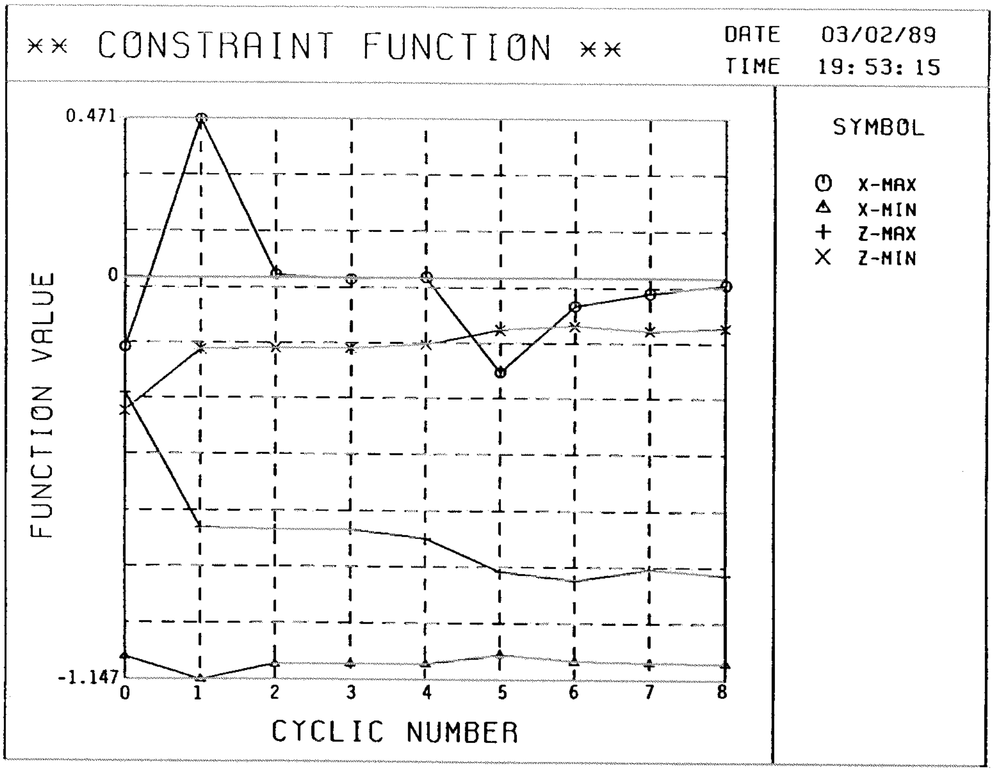

Fig. 9 Constraints iteration history

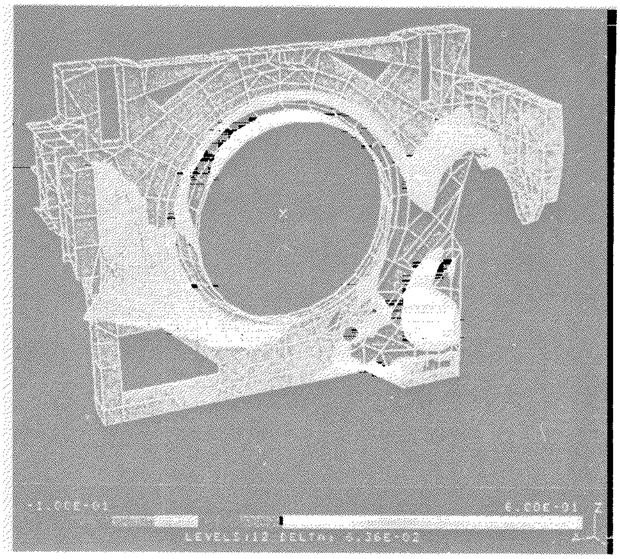

Fig. 10 Original design model

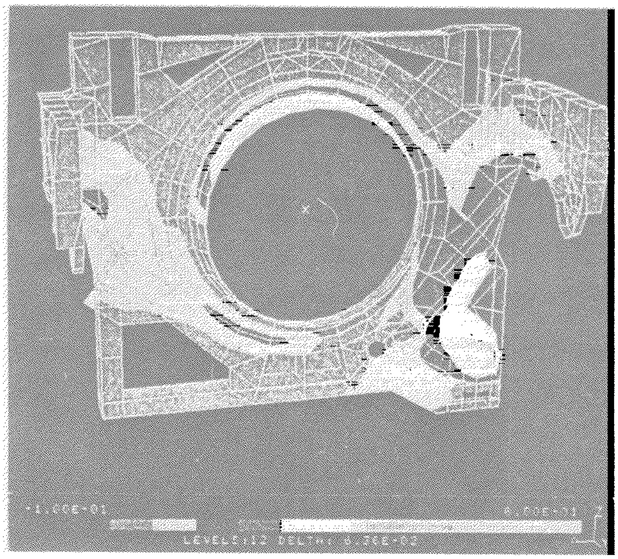

Fig. 11 Optimal design model

CHECK OF STRESS DISTRIBUTION

The stress distributions in the optimal design model were compared with those of the original design. The contour plot of maximum principal stress in the original design is shown in Figure 10, while in the optimal design is shown in Figure 11. The area of high stress in the optimal design was a little larger than the original design. But the stress level was within allowable limits.

CONCLUSIONS

The following conclusions were drawn by solving the optimization problem for CT scanner structure.

(a) When optimal values of many design parameters are searched in order to minimize the object function subject to various constraints, the optimization procedure is very effective. By using the optimization procedure, it is possible to find the unexpected good design modification.

(b) In the structural optimization procedure for practical size problems, the capability of sensitivity analysis in MSC/NASTRAN is very effective and powerful.

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