Zeitschrift: IABSE congress report = Rapport du congrès AIPC = IVBH Kongressbericht

Band: 10 (1976)

Artikel: Structural optimization through sensitivity coefficients

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DOI: https://doi.org/10.5169/seals-10423

Structural Optimization through Sensitivity Coefficients

Optimisation des structures au moyen des coefficients de sensitivité

Optimierung der Tragwerke mittels Sensitivitätskoeffizienten

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1. INTRODUCTION

There are basically two approaches to the solution of a structural optimization problem. In one approach which is followed by Schmit [1] and by Schmit and Fox [2], both kinds of variables namely the design variables and the behaviour variables are treated as unknowns in the programming problem. In the other approach which is followed by Romstadt and Wang [3] and by Vanderplaats and Moses [4] the solution procedure consists of a series of analysis-programming cycles. In each programming stage the most recent set of behaviour variables is treated as known and the design variables are treated as unknowns. The advantage of the first approach is that the programming problem is to be solved only once. The size of the programming problem depends on the number of nodes, the number of members and the number of load conditions. Generally for any practical case the size of the problem becomes almost unmanageable. In the second approach though the programming problem has to be solved many times the size of the problem is smaller. Hence the second approach is preferred to the first.

In the present paper the second approach is followed but the solution procedure consists mostly of solving a series of programming problems. It is observed that in the conventional approach (e.g. that followed by Romstadt and Wang [3]) the time required for the solution of a problem increases rapidly with the increase in the statical indeterminancy of the structure. In such cases the proposed approach is more economical.

2. THEORETICAL ANALYSIS

2.1 Formulation and solution

Formulation of the structural optimization problem as a programming problem has been very well brought out by several authors such as Vanderplaats and Moses [4] or by Brown and Ang [5]. It is therefore assumed here that a structural optimization problem can be formulated as the following non-linear programming problem.

$$\left.\begin{array}{l}\text{Minimize } F(X)\\ \text{Subject to } G_j(X,Y) \leq 0 \quad j=1,\ldots,m\end{array}\right\} \qquad (1)$$

where X is a vector of design variables and Y is a vector of behaviour variables. The objective function can be any function which can be expressed as a function of the design variables. Usually weight of the structure is treated as the objective function. The constraints can be any inequalities which have to be satisfied by the structure such as stress limitations, size limitations or the deflection limitations. In this formulation no distinction is made between the constraints and the restraints.

The optimization process (see fig. 1) is started with an initial set of design variables, X_0. The analysis of the structure (by stiffness matrix method) is carried out to give the associated set of behaviour variables Y_0. After this analysis is over it is found out what is the change in each behaviour variable due to a 100 per cent change in each of the design variables. This information is stored in a matrix called sensitivity matrix which is denoted by CH. A general element CH_{ij} of this matrix stands for the change in i^{th} behaviour variable due to a unit change in j^{th} design variable. The structural optimization problem is then formulated in terms of X_0 and Y_0 to yield new set of design variables $\bar{X}_0$ (see block A). The corresponding set of behaviour variables is now found from the matrix equation

$$Y_1 = Y_0 + CHX(\bar{X}_0 - X_0) \qquad \text{(see block B)}$$

The next programming cycle then makes use of this vector Y_1 to yield new solution of the design variables $\bar{X}_1$. The process thus continues till the difference between the design vectors obtained from two successive programming cycles is found to be smaller than a predetermined vector ϵ. It is clear that the sensitivity coefficients calculated for the initial design will not be useful if the structure is statically indeterminate to a high degree and the original design has undergone a lot of change. In that case the sensitivity coefficients are recalculated (see block C).

The optimization of the structure is thus consisting of mostly the solution of a series of programming problems.

2.2 Calculation of the Sensitivity Coefficients

With the initial set of design variables the stiffness matrix of the structure is assembled in half-band form. If one design parameter is changed by 100 per cent the new stiffness matrix is obtained by recomputing the element stiffness matrix only for one member and then making the appropriate changes in the overall stiffness matrix. Knowing the original set of displacements, the external forces and the new stiffness matrix; new displacements are computed using Jacobi iteration [6]. With new nodal displacements known the new set of behaviour variables and hence the change in each of them due to 100 per cent change in one design variable is computed. These changes when divided by the original value of the design variables give one column of the sensitivity matrix. Before computing the next column the stiffness matrix is reduced to the original matrix.

2.3 Solution of the Programming Problem

The programming problem stated in (1) is solved by using

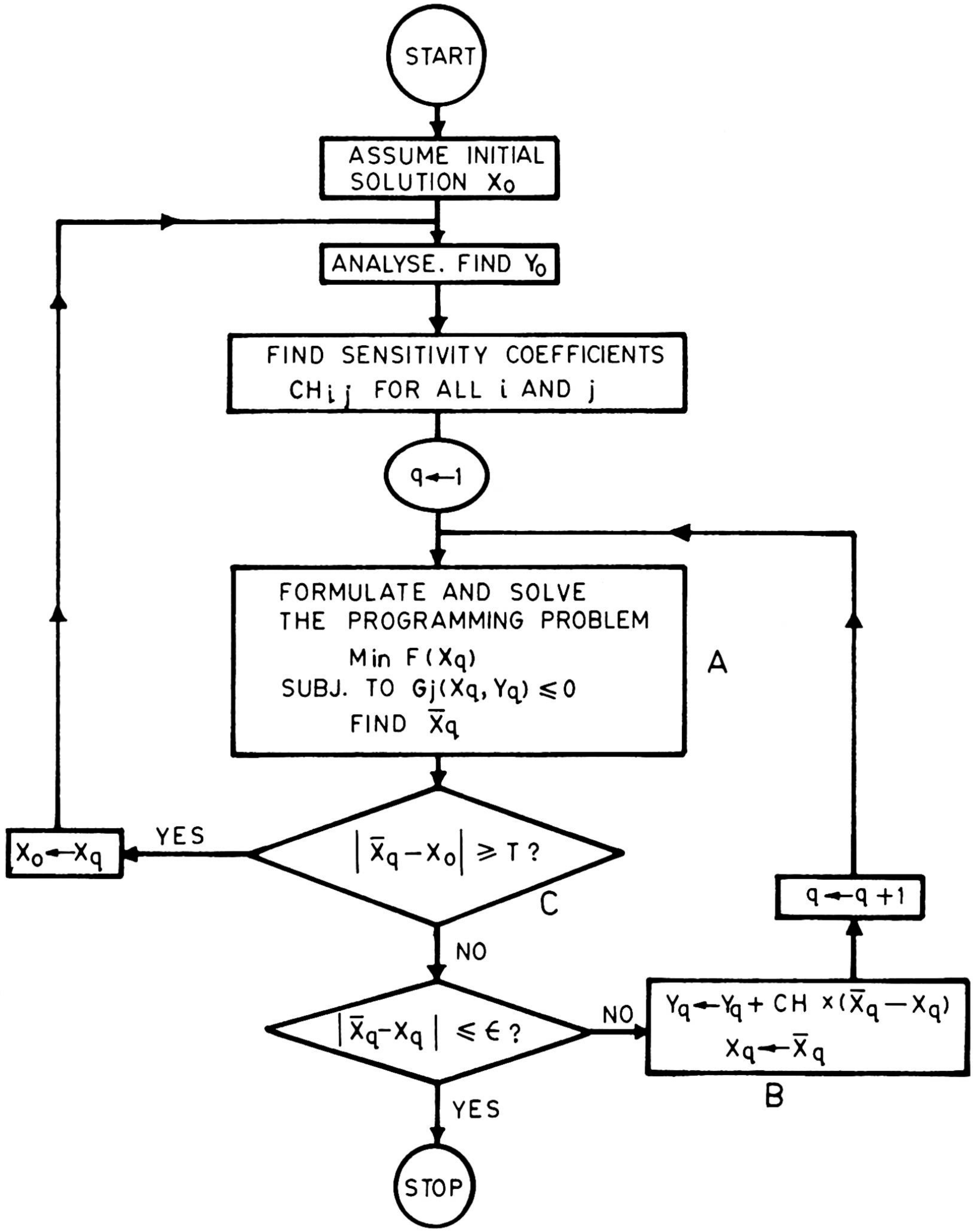

FIG.1. FLOW CHART FOR THE OPTIMIZATION PROCESS

exterior penalty function [6] method which consists of solving a sequence of unconstrained minimization problem:

$$\text{Min } \Phi(X,Y,r) = F(X) + r \langle G_j \rangle^2$$

for increasing values of r which is called penalty. The unconstrained minimization method which is found to be most efficient is the Davidson-Fletcher-Powell [6] method of variable metric and the unidirectional approach that is used is the direct root method. If the number of components in X is large the programming problem given in (1) may not lead to convergence. Hence the vector X is split into subvectors X_1, X_2, ... etc. where each of the subvectors is of a much smaller dimensions than the original vector X [7]. The solution of the programming problem (1) then consists of solving a series of smaller programming problems where only one of the subvectors such as X_1, X_2 are treated as unknowns. The use of exterior penalty function is found to be better when solving such partitioned problems.

3. COMPUTER PROGRAMMING AND NUMERICAL WORK

A general computer program based on the proposed method is written separately for trusses and for frames. The program is written in FØRTRAN IV language and is compatible with IBM 360, CDC 3600, DEC 10 and EC 1030 (called Ryad in some countries) computer systems. Several truss and frame problems for minimum weight design have been solved.

4. CONCLUSIONS

A general optimization algorithm for any structural problem has been suggested.

Acknowledgement

The author is extremely thankful to Prof. C.K. Ramesh, Civil Engineering Department, Indian Institute of Technology, Bombay for his encouragement and guidance.

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SUMMARY

Structural optimization problem is generally solved as a sequence of analysis-programming cycles. In this paper it is shown how this problem can be treated as a series of programming problems. The relation between the changes in the behaviour variables due to a specified change in each of the design variables is found and stored in the form of "Sensitivity Matrix". This matrix directly gives the solution corresponding to a given set of design variables. The availability of this matrix dispenses with the frequent analysis.

RESUME

Le problème d'optimisation des structures est résolu généralement par une série de cycles dans un programme de calcul. On montre comment ce problème peut être traité par une série de problèmes de programmation. La relation entre les changements des variables de comportement et ceux de l'une quelconque des variables du projet est determinée et compilée sous forme de "matrice de sensitivité". Cette matrice donne directement la solution correspondant à un ensemble donné de variables du projet. On peut donc éliminer avec cette matrice de nombreux calculs.

ZUSAMMENFASSUNG

Das Problem der Optimierung von Strukturen wird allgemein als eine Reihe von analytischen Programmierungszyklen gelöst. Im vorgelegten Beitrag wird gezeigt, wie die allgemeine Methode der Optimierung als eine Reihe von Programmierungsproblemen behandelt werden kann. Die Beziehungen zwischen den Verhaltensvariablen und den Entwurfsvariablen werden hergestellt und als "Sensitivitätsmatrix" gespeichert. Aus dieser Matrix ergibt sich direkt die der gegebenen Gruppe von Entwurfsvariablen entsprechende Lösung. Die Benützung dieser Matrix vermeidet eine Wiederholung der Berechnung.

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