1998

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COMPRESSOR COMPONENTS OPTIMIZATION WITH THE USE OF FINITE ELEMENT METHOD

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ABSTRACT

During the design of a compressor with the use of the finite element method, some steps are followed, such as an initial design, analysis, results evaluation, and design adjustment. All the steps are repeated in a process where the experience of the designer is very important to get good results. Many times, the optimum design is not achieved due to the time required to perform repeatedly all the steps. Another and more efficient technique to do the same job is to integrate all the development cycle in a mathematical method. After the definition of an optimization function, and the main constraints, the method is able to find the optimum design, automatically and efficiently.

To illustrate the application of the optimization method, a design of a discharge tube for compressor will be presented. The problem consists in determine which is the best design for the tube in terms of raw material cost (minimum length). The design must respect two constrains: the running frequency and the material stress limit.

INTRODUCTION

A design is the configuration of a part, product, or structure that enables a specified function to be performed [1,2].

An optimum design is the one in which some aspects such as weight, manufacturing cost, or performance are improved to the greatest extent possible without compromising the intended function. By optimum design, it means one that meets all specified requirements, but with a minimum expense of certain factors such as weight, surface area, volume, stress, cost, etc. In other words, the optimum design is usually one that is as effective as possible. Virtually, any design aspect can be optimized: dimensions (such as thickness), shape (such as fillet radii), supports placement, manufacturing cost, natural frequency, material properties, and so on. An optimum design is best only in terms of the design problem explicitly specified. That is, optimum is a relative term and does not imply that all factors have been taken into account.

Traditionally, an optimum design has often been costly and time consuming to achieve. It is usually pursued through a manual design process in which the engineer:

1. Develops an initial design
2. Performs the design analysis
3. Evaluates the analysis results
4. Modifies the design
5. Repeats 2, 3 and 4 until an optimum is obtained
Each repetition of these steps is called a design cycle or optimization loop. This process has traditionally been linked together and controlled in hands-on fashion by the engineer (figure 01). Because of the expense and time involved in pursuing an optimum design by a traditional approach, a less than optimum design is often accepted in an economic trade-off.

Design optimization is a programmed mathematical technique that integrates the design cycle into an intelligent automated process to seek the optimum design (figure 02).

**BASIC DEFINITIONS AND OPTIMIZATION METHODS**

Before describing the procedure for design optimization, it will be necessary define some of the terminology: design variable, state variable, objective function, feasible and infeasible design [3].

**Design variables**: are independent quantities that can be varied in order to achieve the optimum design. Upper and lower limits are specified to serve as "constraints" on the design variables.

**State variables**: are quantities that constraint the design. They are also known as "dependent variables", and are typically response quantities that are functions of the design variables. A state variable may have a maximum and minimum limit, or it may be single sided, having only one limit.

**Objective function**: is the dependent variable to be minimized. It should be a function of the design variables, that is, a change in the values of the design variables should change the value of the objective function.

**Feasible design**: is one that satisfies all specified constrains (constrains on the state variables as well as constrains on the design variables). If one of the constraints is not satisfied, the design is considered Infeasible.

During design optimization, two mathematical methods will be used:

**Subproblem Approximation Method**: this is an advanced zero-order method that uses approximations (curve fitting) to all dependent variables;

**First Order Method**: this method uses derivative information, that is, gradients of the dependent variables with respect to the design variables. It is highly accurate and works well for problems having dependent variables that vary widely over a large range of design space. However, this method can be computationally intense.

It is out of the scope of this paper to present mathematical details about the two methods. A complete set of information can be found in [4].

**DESIGN OPTIMIZATION AND FINITE ELEMENT ANALYSIS**

The application of design optimization together with FEA (finite element analysis), is a powerful way to improve the compressor components design. To illustrate the use of the both tools simultaneously, it will be presented the design of a discharge tube for compressor. All the process (FEA and design optimization) is made with the use of commercial software.

The first step of the design is to build a parametric model for the tube. Just in this way, design optimization will run in the adequate manner, where the changes can be done...
automatically. For this design, it will be used an Archimedes spirals shape for the tube. Figure 03 shows a sketch for the tube. The geometrical equation for the spiral is:

\[ R = A \theta \]

where:
- \( R \) = radius
- \( A \) = geometrical coefficient
- \( \theta \) = angle.

The two constraints for the design are: to avoid the tube first natural frequency being in the range of running frequency; and that the tube during the operation or transportation respects the limits on stress. The objective function is to find the best design in terms of row material cost (the minimum tube length). The set of data for this design optimization process is:

- Design variable (DV): \( A \) (minimum value = 0.2, maximum value = 1.3)
- State variables (SV): \( \text{FREQ1} \) - first natural frequency (minimum value = 70), \( \text{SEQVMAX} \) - Von Mises stress (maximum value = 60000)
- Objective function (OBJ): \( \text{LCOMP} \) - tube length. (minimize)

The table I presents the results for each loop of the design optimization, using the first order method, with defaults values for tolerances. The same problem is solved with the subproblem approximation method, also with default values (table II). The results show that the second method is more adequate to optimize this problem, in terms of the minimum length and CPU run time. The subproblem approximation method consumed just 23% of the time expended for the first order method, and found a length 2.6% lower (a double advantage). If you reduce the tolerance of the length by half for the first order, you will find almost the same value for the length, but the CPU run time will increase 14.6 times (see table III).

Otherwise, independently of the method used, the process conduct to an optimum design automatically, in an efficient way.

**CONCLUSIONS**

The use of design optimization together with FEA is a powerful tool to improve the compressor components design. Among many applications, as well as to reduce cost, it can be used to design a component with specific characteristics, such as, frequency, minimum weight, minimum temperature in heat transfer, maximum peak torque in magnetic motor design, or tolerance analysis. Another important advantage of the use of design optimization method is to reduce the development time.

Design optimization shall not be considered as a magic box. It depends a lot on the problem formulation quality. The optimum is just function of the design variables considered. The knowledge of the methods is very important to achieve really the “optimum” design, avoiding local minimum. The problem must be as simple as possible, to reduce the CPU run time. The main difficulty to use design optimization is to build a parametric model. This problem can be solved with the integration of CAD together with FEA software.
REFERENCES

1. Design Optimization Seminar, revision 5.0, SAS IP, Inc.

Figure 01 – The traditional process for design optimization
Design Optimization

Initial Design

Optimum Design

Figure 02 – The mathematical process for design optimization

Figure 03 – The Archimedes spiral shape for the discharge tube
### Table I – First Order Method  
**CPU run time = 77.24 sec**

<table>
<thead>
<tr>
<th></th>
<th>SET 1 (INFEASIBLE)</th>
<th>SET 2 (FEASIBLE)</th>
<th>SET 3 (FEASIBLE)</th>
<th>SET 4 (FEASIBLE)</th>
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<tbody>
<tr>
<td>FREQ1 (SV)</td>
<td>119.64</td>
<td>74.231</td>
<td>73.850</td>
<td>74.777</td>
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<tr>
<td>SEQVMAX (SV)</td>
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<td>57053.</td>
<td>56780.</td>
<td>57445.</td>
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<td>A (DV)</td>
<td>0.70000</td>
<td>0.52077</td>
<td>0.51916</td>
<td>0.52309</td>
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<tr>
<td>LCOMP (OBJ)</td>
<td>330.85</td>
<td>418.61</td>
<td>413.69</td>
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### Table II – Subproblem Approximation Method  
**CPU run time = 17.59 sec**

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### Table III – First Order Method  
**CPU run time = 256.7 sec**

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