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Interval-based global optimization in engineering using model reformulation and constraint propagation

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ABSTRACT

This paper deals with the preliminary design problem when the product is modeled as an analytic model. The analytic models based method aims to use mathematical equations to address both multi-physic and economic characteristics of a product. The proposed approach is to convert the preliminary design problem into a global constrained optimization problem. The objective is to develop powerful optimization methods enough to handle complex analytical models. We propose to adapt an approach to solve this problem based on interval analysis, constraint propagation and model reformulation. In order to understand the optimization algorithm used for engineering design problems, some basic definitions and properties of interval analysis are introduced. Then, the basic optimization algorithms for both unconstrained and constrained problems are introduced and illustrated. The next section introduces the reformulation technique as main accelerating device. An application of the reformulation device and its global optimization algorithm on the optimal design of electrical actuators is presented.

1. Introduction

Global optimization is an important issue in the field of product engineering allowing to reduce costs, to improve product performance, reliability and shorten design time. The objective of this paper is to develop powerful optimization algorithms enough to handle complex engineering problems and particularly electromagnetic devices (electric actuators).

Many authors worked on the design theory and proposed several descriptions of the design process. The systematic design approach proposed by Pahl et al. (2007) and described in Fig. 1 is one of the most used design theory. The main task of the design engineers is to propose an "optimal" design solution satisfying all the customer needs. The feasibility of a technical solution is related to the constraints satisfaction including technological, economic, environmental and legal aspects. The optimization step is performed according to one or more criteria (economic, performances, etc.).

Fig. 1 shows the design steps proposed by Pahl et al. (2007) related to the design of an electric actuator. Firstly, the customer needs are expressed through the specifications, in which some constraints are imposed. Generally, these constraints are related to the product performances, dimensions and/or the materials. Then, these needs are analyzed, adapted if necessary and validated. As the electric actuator is a well known concept, the mathematical model expressing its physical behavior is known. According to the classification of Gero (2001), the example of the electric actuator design belongs to the routine design class. The next step consists in formulating the final analytical model that takes the specifications' constraints into account. During the preliminary design step, a first quantification of the design parameters is given using an optimization tool. The most used method to get a first design solution is the Finite Elements Method (FEM). But this complex method is becoming more and more inappropriate during the preliminary design since it is based on the device geometry. Thus, the multi-physic behavior and the economic objectives are poorly managed and the computations are time-consuming. Let us take, as example, the electromagnetic actuator design problem. This kind of product involves simultaneously the electromagnetic, the mechanical and the heat fields. Therefore, in order to describe the physical behavior of the electromagnetic actuator, it is necessary to solve complex partial differential equations: Maxwell equations for the electromagnetic behavior, the heat equations for the heat behavior and so on. Generally, design engineers make assumptions in order to integrate those equations and get consequently analytic equations that explicitly link the product performances to the

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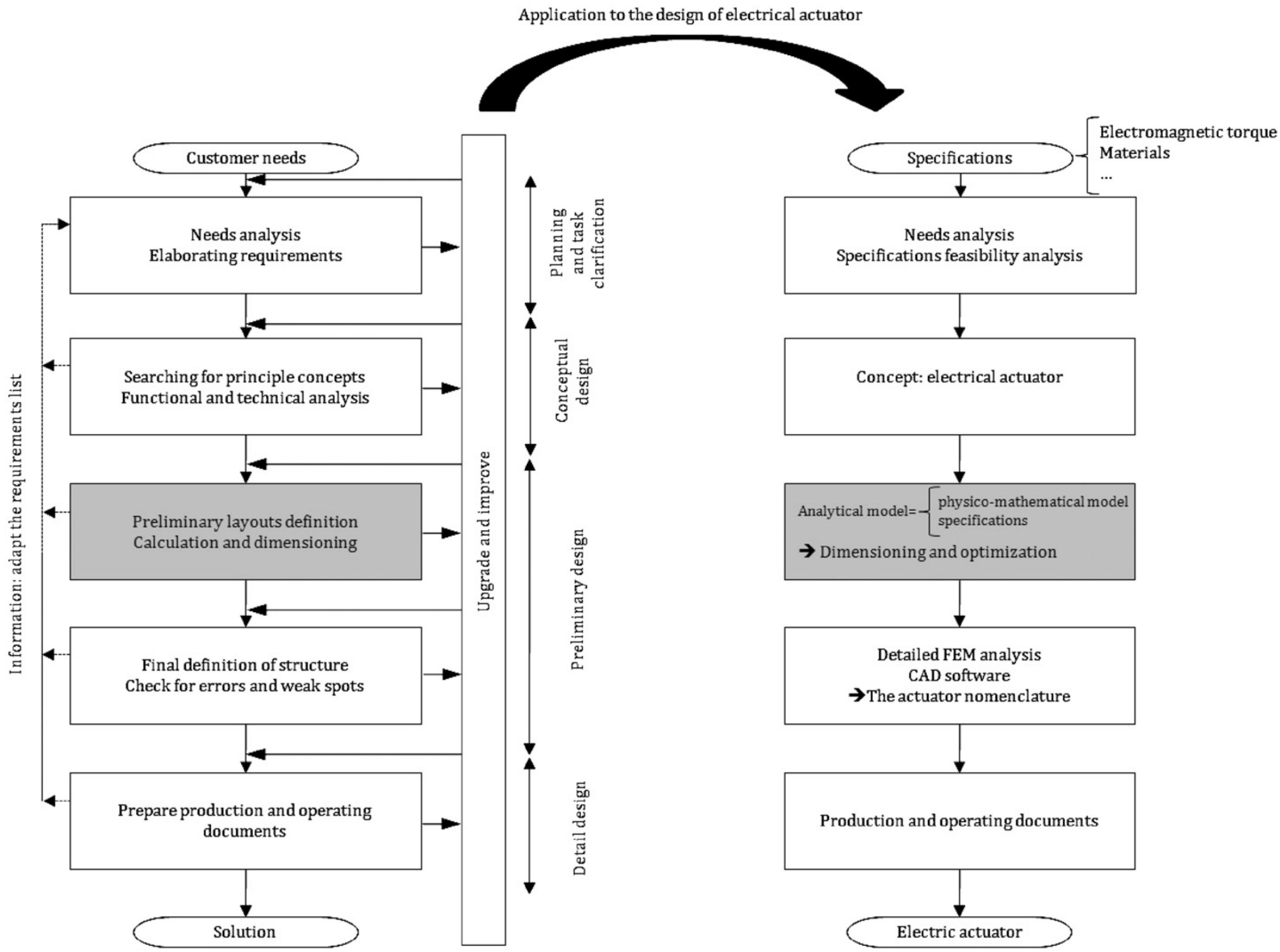

Fig. 1. Simplified steps of the design process (Pahl et al., 2007).

design parameters. Roters gives in Roters (1941), a set of analytic equations based on simplifying assumptions for the electromagnetic devices. This is all the more interesting as the customer specifications generally deal with the geometry, the materials and the performances parameters simultaneously. Unlike the FEM method, the analytic models based method aims to use mathematical equations describing the technical and the economic characteristics of the device. These models respond to the preliminary design complexity and the use of a global optimization approach aims to build an initial design solution.

The final definition of the structure is validated using a CAD software and an FEM analysis of the design solution. Finally, the production and operating documents are prepared.

This paper deals with the first step of the preliminary design step: computation and dimensioning. It attempts to propose an optimization tool adapted to a wide range of design problems. This tool is particularly suitable for the routine design as the analytic models are generally available. During the preliminary design step also called embodiment design, the concepts selected during the conceptual design step starts to materialize the product and the preliminary layouts are generated. These layouts are then optimized and several criteria could be used to evaluate them in order to select the most promising. Finally, the selected layout will be the object of a detailed design. Consequently, an important part of the product costs is incurred in the preliminary design step. Thus, it is important to use an optimization tool.

The selection of the solving algorithm is extremely important. This will be guided by the problem formulation and the expected results. Numerous optimization techniques could be used at the preliminary design step. These techniques may be classified according to two criteria: the operating approach (stochastic or deterministic) and the quality of the solution sought (local or global). Many authors worked on design optimization using stochastic approaches. Isfahani and Vaez-Sadeh (2007), Ahn et al. (2003) and Ho et al. (2008) applied a Genetic Algorithm to the design of engineering devices: electric motors and squeeze film damper. Pierre et al. (1995) applied a Simulated Annealing algorithm for the optimal design of a computer communication network. He and Wang (2007) proposed a Particle Swarm Optimization for constrained engineering design problems. The advantage of the stochastic algorithms is their wide range applicability and their implementation simplicity. Indeed, the objective function and the constraints are not required to be linear, convex, differentiable and continuous. Nevertheless, these algorithms do not give optimality neither feasibility proofs. In addition, they need some parameters setting which may affect the algorithm convergence.

Deterministic algorithms have also been used in engineering design. Gol and Sobhi-Najafbadi (2005) and Lin and Lin (2001) used the Sequential Quadratic Programming local algorithm for the optimal design of, respectively, electromotion devices and rotor systems. The main drawback of the local methods is that