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Merit exponents and control area diagrams in materials selection

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ABSTRACT

Merit indices play a fundamental role in materials selection, since they enable ranking of materials. However, the conventional formulation of merit indices is associated with severe limitations. They are dependent on the explicit solution of the variables in the equations for the constraints from the design criteria. Furthermore, it is not always easy to determine which the controlling merit index is. To enable the ranking of materials in more general design cases, merit exponents are introduced as generalisations of the merit indices. Procedures are presented for how to compute the merit exponents numerically without having to solve equations algebraically. Merit exponents (and indices) are only valid in a certain range of property values. To simplify the identification of the controlling merit exponent, it is suggested that so called control area diagrams are used. These diagrams consist of a number of domains, each showing the active constraints and the controlling merit exponent. It is shown that the merit exponents play a crucial role when the control area diagram (CAD) is set up. The principles in the paper are developed for mechanically loaded components and are illustrated for engineering beams with two or three geometric variables.

1. Introduction

When selecting a material it is not uncommon to make a conservative choice, by selecting a material that has been used for a similar situation before. This leads to a rather narrow selection and will typically not lead to the optimal material. The need for systematic materials selection is obvious from the vast number of engineering materials that are available. According to Ashby [1] there were in 1992 more than 80,000 material to choose between. There are in principal two kinds of situations to handle. In the first case the component geometry is fixed and the least expensive material that fulfils all the property requirements is selected. In the second case, the geometry and the choice of material are adapted to each other. In this latter case, the natural technique to be used is structural optimisation [2].

The procedure for materials optimisation in mechanical design is divided into two parts, one discriminating (or de-selection) and one optimising part [1,3]. The former includes property requirements that have to be fulfilled, which do not influence the final dimensions of the component. Discriminating material properties can be divided into three general types; one for usage, one for manufacturing and one for availability. Usage restrictions could be due to the environment or physical performances that have to be fulfilled. An aggressive environment gives for example requirements on corrosion and oxidation properties, the temperature capability of the material, etc. A heat exchanger would have demands on the thermal conductivity. Manufacturing also gives rise to a number of demands on properties. Such discriminating properties could be weldability and machinability. A harder material is more difficult to form and machine requiring more advanced manufacturing techniques. Availability of the material at reasonable costs is also an important aspect.

In this paper we will only deal with the optimisation part, where we should simultaneously find the optimum geometry and material. The use of merit indices to rank materials has greatly increased the understanding of materials selection. There are many names for merit indices in the literature, such as merit parameters and figures of merits. The first to use merit indices may have been Farag [4]. Another text where the merit indices were used in some form was the text by Charles and Crane [5]. Some of the early works are studies on thermal fatigue of brittle materials [6,7]. Sandström was the first to use merit indices in material optimisation when competing design criteria are involved [8]. In addition the import merit index for the geometric constraints was introduced. These results were later generalised [9]. In mechanical design one main issue is to know which merit index to select and how the design parameters affect this choice. Sandström developed what he called control area diagrams to greatly simplify the selection of merit index [10]. Ashby illustrated the use of merit indices in an elegant way in the form of charts [11,12].

In spite of the values of the merit indices there are important limitations in their usage. The present way of deriving them is based on the possibility of getting explicit expressions of the

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