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Optimal mass minimization design of a two-stage coaxial helical speed reducer with Genetic Algorithms

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ABSTRACT

The full description of a two-stage speed reducer generally requires a large number of design variables (typically, well over ten), resulting a very large and heavily constrained design space. This paper presents the specific case of the complete automated optimal design with Genetic Algorithms of a two-stage helical coaxial speed reducer. The objective function (i.e. the mass of the entire speed reducer) was described by a set of 17 mixed design variables (i.e. integer, discrete and real) and also was subjected to 76 highly non-linear constraints. It can be observed that the proposed Genetic Algorithm offers better design solutions as compared with the results obtained by using the traditional design method (i.e. a commonly trial and cut error).

1. Introduction

The design problem of a mechanical power transmission such as a two-stage helical coaxial speed reducer is a complex process involving a number of challenges, particularly when considering the multiple interdependencies between the design variables defining its subsystems (i.e. the gearings, the shafts-subassembly, and the housing-case and cover). In other words, an optimal reducer is generally not an assembly of components optimized in isolation, a fact overlooked by many conventional design heuristics [1]. The optimization of the complete speed reducer leads to a complicated objective function, with a large number of design variables of mixed nature (i.e. integer values-for gears number of teeth, discrete values-for normal tooth addendum coefficients and real values-for gears width) and highly non-linear constraints. Moreover to design means to make decisions, which unfortunately are always compromises. A typical example might be that selecting a smaller than optimal gear diameter (and a correspondingly greater contact width) could yield a somewhat heavier gearing, but a more compact layout and therefore a much lighter housing; it is worth mentioning though that in reality the impact on the overall objective tends to be much less direct and therefore much more obscure than in this example [1]. It is clearly that it is almost impossible to tell what the first compromise should have been, let alone what any subsequent choices should have been made with the overall goal in mind. If we take into account all the above facts, it is obviously that the traditional design (for such a complex problem) is a very difficult process, so the computer aided design of the gears is needed. Anyway, a more pronounced increase demands for compact, efficiency, and reliable gears have forced the designer to use the optimal design methodology [2]. In the last decades many researchers have paid attention on this problem of gear optimization. Madhusudan and Vijayasimha in [3] presented a computer program in order to design a required type of gear under a specified set of working conditions. In [4] a new computer-aided method for automated gearbox design is described. Huang et al. developed an interactive physical programming in order to optimize a three-stage spur gear reduction unit [5]. Abersek et al. in [6] described an expert system to design and manufacture a gearbox. Li et al. [7] reported a study for minimizing the center distance of a helical gear using American Gear Manufacturers Association (AGMA) procedures. Yokota et al. in [8] solved an optimal weight design problem of a gear with an improved Genetic Algorithm (GA). Deb and Sachin, in [9] used a non-dominated sorting Genetic Algorithm (NSGA-II) in order to solve a multi-objective optimization of a multi-speed gearbox. Thompson et al. [10] presented a generalized optimal design of two-stage and three-stage spur gear reduction units in a formulation with multiple objectives. Ray and Saini illustrated in [11] the benefits of the particle swarm searches in resolving different engineering designs. In [2] Savsani et al. presented two advanced optimization algorithms known as particle

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swarm optimization (PSO) and simulated annealing (SA) in order to minimize the weight of a spur gear train. The results of the proposed algorithms were compared with the results obtained by Yokota et al. [8]. Gologlu and Zeyveli in [12] applied GA to minimize the volume of a two-stage helical gear train. A design methodology for two-stage speed gearboxes is presented in [13]. These studies referenced above have been instrumented in order to highlight two important aspects regarding the topic of this work.

Firstly, it is obvious that all the authors cited above applied the optimization techniques for individual components (only gears or shafts) or intermediate assemblies rather than to the entire speed reducer (considering the multiple connections between its subsystems, i.e. the gearings, the shafts-subassembly, and the housing). In the same vein and in order to find out which are the dimensional tendencies of the speed reducer's components and how the functional and structural interdependencies affect them we decomposed the optimal design problem into a set of *two tractable subproblems*. So we dealt separately with the *gearings* [14] and *the shafts* [15]. In this way we could take the correct and necessary decisions for the complex and difficult *optimal design of the complete speed reducer* [1]. In [1] we minimized the mass of the entire speed reducer using a two-phase evolutionary algorithm, based on the paradigm of '*punctuated equilibra*', i.e. a phenomenon associated by some biologists with the so-called *Cambrian explosion*, a time of rapidly increasing genetic diversity.

Secondly, these studies emphasize the importance of using modern global optimization techniques in the mechanical power transmission design (as opposite to conventional, trail and error type methods), even when considering certain components (i.e. gears, shafts etc.).

In order to ***build a generic transmission system design tool based on the evolutionary optimization concepts*** [1] in this paper we successfully managed to optimal design a *new*, *complex* and *interesting layout* (see for example Fig. 1) of a two-stage speed reducer (i.e. a *coaxial one*-which means the input and output shafts are *collinear* – Fig. 2). This new layout introduces a number of challenges (considering the center distance for both stages has the same value) as opposite to the example presented in Tudose et al. [1]. Moreover, as opposite to previous reminded optimal design, in here we considered new materials for all four gears (i.e. case hardened alloy steel as it can be observed in Section 5) and a new set of input data.

We shall now introduce the traditional speed reducer design method (currently used for designing a multi-stage power transmission – Section 2), after which we describe the general principle of the proposed Genetic Algorithm (Section 3), followed by a detailed discussion regarding the statement of the optimal design problem (the objective function, the design variables and the constraints – Section 4). The fifth Section contains an effective example and a detailed presentation and comparison of the numerical results for optimal and traditional design (i.e. a commonly trial and cut error procedure) solutions. Eventually, we conclude this discussion with some reflections and suggestions regarding the possible extensions of the present study.

2. Traditional speed reducer design overview

The traditional speed reducer design process depends on the designer's intuition, experience, and skills [16]. The flowchart of a traditional speed reducer design is presented in Fig. 1. As one can notice, there are 3 distinct, though interdependent sections, necessaries to design the entire speed reducer. In the following a description of each section is presented. The first section consists in **gearing design**. The main difficulty that arises in traditional gear set design lies in the fact that it is necessary to know all the dimensions of the gears, as well as the tooth form and size, before the loads and stresses may be accurately determined. This makes it necessary to *estimate* the size of the gears (i.e. steps -1*a*- through -1*i*- from Fig. 1), using simplified methods, and then to *check* the estimate, using the various design factors (K_v, $K_{H\beta}$, $K_{H\alpha}$, Z_ε, Z_H, Z_β, $K_{F\beta}$, $K_{F\alpha}$, Y_{Fa}, Y_{Sa} and Y_β; German Industrial Standard (DIN) 3990 [17]) in conjunction with more exact equations (i.e. steps -1*j*- through -1*r*- from Fig. 1). The estimated size and tooth form are then altered in accordance with the information obtained from the exact equations [18]. Let us now present the steps (pointed out in the above rows) used in gear design [17,19,20]. It is well

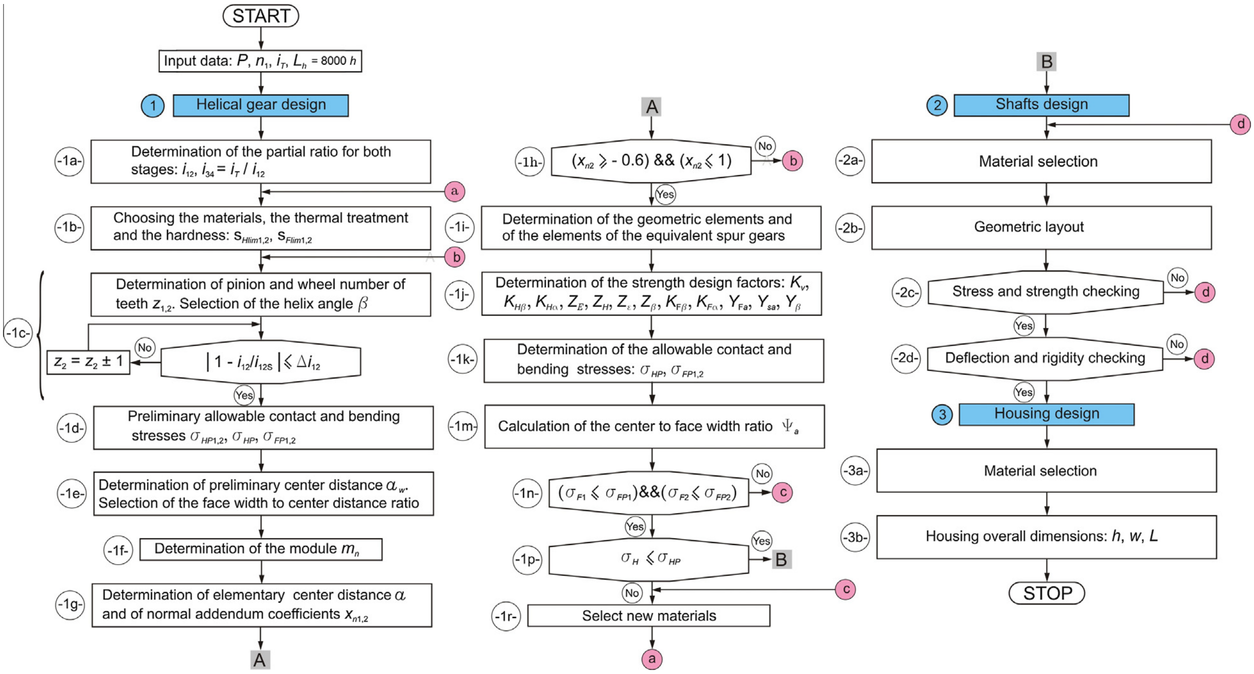

Fig. 1. The flowchart of a traditional speed-reducer design.