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Development of an engine crankshaft in a framework of computer-aided innovation

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ABSTRACT

This paper describes the conceptual framework of a general strategy for developing an engine crankshaft based on computer-aided innovation, together with an introduction to the methodologies from which our strategy evolves. It begins with a description of two already popular disciplines, which have their roots in computer science and natural evolution: evolutionary design (ED) and genetic algorithms (GAs). A description of some optimization processes in the field of mechanical design is also presented. We explain our approach to multi-objective optimization and show how tools like the Pareto diagram can help in identifying conflicts. The concepts presented here are exemplified through the optimization of a combustion engine crankshaft. The main premise of the paper is the possibility to optimize the imbalance of a crankshaft using tools developed in this methodology. This study brings together techniques that have their origins in the fields of optimization and new tools for innovation. We reflect on how computers can have an active role in the conceptual design process, and explain how TRIZ (Theory of Inventive Problem Solving) can enrich the discipline of ED. The aim of our research is to extend the search for solutions with GAs and present creative, innovative alternatives to the designer. Similarities between GAs and TRIZ regarding ideality and evolution are presented. We also explain how geometric optimization systems (size, shape, topology and topography) offer hints about the next generation of optimization tools. The role of splines in this context is found to be closely integrated with GAs in enabling this development on a computer-aided design and engineering (CAD&CAE) software interface, and in enabling integration with Java programming language for automation of the development.

1. Introduction

The usefulness of computers in product design ranges from data management, drawing, analysis, and simulation to numerous other applications. Computers are programmed to do what humans intend and are capable of performing far beyond the abilities of the most skilled designer. In the world of mechanical design, software tools are used for a large number of applications, from modelling and optimization tasks to simulating the performance of a product. This allows the engineering designer to concentrate on activities related to software analysis, prototype testing, creativity and innovation. Computer-aided innovation uses software tools to provide extended support for the creative part of the design process. With this support, the designer can improve the performance of his or her concepts, letting computers take part not only in generating variants, but also in making judgments, by simulation, of these variants. Thus, a designer can explore numerous creative solutions to problems (overcoming 'design fixation' or the limitations of conventional wisdom) by generating alternative solutions. Software tools can use knowledge from designers to generate new solutions based on many separate ideas and suggest entirely new design concepts. Methods for structural and topological optimization, based on evolutionary algorithms, are used to obtain optimal geometric solutions. They evolve into configurations that minimize the cost of trial and error.

The case study is selected in view of the importance of motor crankshafts in the automotive industry [1] and the increased performance requirements for engines, which have increased the production of forged steel crankshafts worldwide. Imbalance, one of the quality parameters of crankshafts, has a significant impact on the life of the entire system. In the forging process, given the variations of material composition, temperature, etc., the imbalance dispersion increases compared to casting crankshafts. It is of particular importance to reduce this variation right from the conceptual design of the crankshaft. The authors have written a series of articles related to this problem from various perspectives

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using a range of tools [2,3]. The work continues, with a general description of the project as a step forward towards improving the strategy.

1.1. General goal (general objective of the proposed research)

The goals of the study are, first, to construct a strategy for developing engine crankshafts based on a framework of computer-aided innovation; and second, to lay the foundations for a research topic about computer-aided innovation that uses:

- CAD and CAE tools as an interface to the designer,
- genetic algorithms as the main optimization/innovation mechanism,
- TRIZ to extend the breadth of the evolutionary operators, and
- splines for shape construction.

All of this takes place in an automated environment allowing computers to push designers to reach the boundaries of creativity by helping them overcome design fixation when optimizing. A range of disciplines converge to form the foundation of this research topic in computer-aided innovation. Without any particular order, a brief description of them follows.

1.2. Evolutionary design

A relatively new area of development called evolutionary design [4] has become an object of intensive research. Peter Bentley describes evolutionary design as a process capable of generating designs by changing shapes and topologies. Consequently, an intricate design can arise through a slow, gradual, mindless improvement process. Evolutionary design mimics the way nature behaves by using evolutionary algorithms that change the forms and topologies of the design object.

Biological creatures far exceed the products created by humans in terms of complexity and performance. This idea has created a brand in design referred to as biomimetic (emulating biology).

Evolutionary design has its roots in computer science, design, and evolutionary biology. It extends and combines CAD and analysis software, and borrows ideas from natural evolution. The use of evolutionary computation to generate designs has taken place in many different fields since the late 1980s [5]. Designers have optimized selected parts of their designs using evolutionary computation [6]. Although the field of evolutionary design is showing some impressive results, computers are not fully autonomous. People are required to work out which function the design should perform, and how a computer should be applied to the problem. Evolutionary design can present characteristics that add value to the product, even by chance. If the creations of design concepts evolve generating novel designs, e.g. novel product shapes that achieve higher performance, this can be interpreted as "being creative". Therefore, it can be said that computers can present "creative" behaviour [7].

1.3. Genetic algorithms

Genetic algorithms (GAs) are adaptive, heuristic search algorithms (stochastic search techniques) based on the ideas of evolutionary natural selection and genetics [8]. They are used to find approximate solutions to optimization problems. The basic concept of GAs is aimed at simulating processes in natural systems that are necessary for the mechanics of evolution, specifically, those processes that follow the principles proposed by Charles Darwin: the "law of the strongest" or the "survival of the fittest". They represent an intelligent exploitation of a random search within a defined search area to find a solution. Genetic algorithms are typically used in computer simulation, from which a population of abstract representations (called chromosomes) of possible solutions (called individuals) are applied to a design problem that evolves towards the best solutions. Traditionally, the solutions are represented in binary code as strings of 0s and 1s, but different codes are also possible. The evolution begins with a population of random individuals and produces results in generations. In each generation, the fitness of the entire population is evaluated, many individuals are chosen stochastically from the current population (based on their fitness), modified (mutated or recombined), and form a new population. This new population is used in the next iteration of the algorithm. Genetic algorithms have been studied extensively and have been applied in many fields of engineering. Many real-world problems involving a search for optimal parameters may be hard to solve with traditional methods, but when GAs are used, the solution is more easily found. However, due to their outstanding performance in optimization, GAs have been wrongly regarded as a tool only for optimization. Genetic algorithms also show impressive results compared to other search engines, and for this reason, the authors perceive them as a potential tool for creativity enhancement.

1.4. Design optimization systems

The evolution of product development tools has been characterized by various trends, and the analysis of these trends offers useful hints for predicting next generation systems. The optimization of products and processes has been studied since the spread of computers as an aid for seeking "optimal" forms and shapes of product geometry. In the mechanical field, geometric parameterization is used to define the kind of changes described by design variables. Particularly, two kinds of structural optimization are frequently used: topology optimization and shape optimization.

Topology optimization tries to achieve the maximum ratio between volume and some geometrical parameters. It determines the optimal material distribution within a given design space. For example, it takes out the elements under low stress in geometry by modifying the apparent material density, considered a design variable in a FEM model. A basic FE model is created and analyzed in a design area with given boundary conditions. Commonly, the aims are to maximize stiffness or maximize the natural frequency of a product. The constraints of the design are the fixations, material volume, and maximum displacement allowed. The design variables are the material density of the elements, which are counted usually in hundreds of thousands; this means a huge number of design variables. The goal, given a predefined design domain in the 2D/3D space with structural boundary conditions and load definitions, is to distribute a given mass, which is a given percentage of the initial mass in the domain determined in such a way that a global measure takes a minimum (maximum) value. This type of topology variation is outside the scope of this paper but is also being analyzed by the authors and will be presented in future publications.

Shape optimization consists of changing the external borders of a mechanical component. The geometry of the product is defined in terms of surfaces and curve parameters that define the outer boundary of the product and allow more freedom to manipulate. Here, too, the topology remains unchanged. The shape of the structure is modified by the node locations of a product modelled with the finite element method (FEM). The aims are to minimize the stress or the volume or maximize the natural frequency. Constraints to the design include fixations and restrictions for displacement of component borders. The design variables of the product for geometric models are length, angle, and radii measurements; and for FE models, node coordinates.