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Efficient design optimization of complex system through an integrated interface using symbolic computation

Hansu Kim, Shinyu Kim, Taekyun Kim, Tae Hee Lee*, Namhee Ryu, Kihan Kwon, Seungjae Min

Department of Automotive Engineering, Hanyang University, Seoul, Republic of Korea

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ABSTRACT

A complex system is composed of several subsystems and numerous lower level components. It is inefficient to design the complex system at the system level by using high-fidelity models. A system level approach using a language-based model is required to design such a highly complex system before implementing a detailed design. However, as commercial process integration and design optimization software packages focus on detailed design, which uses the high-fidelity models, it is difficult to perform the design optimization of a highly complex system, such as a combat vehicle. Moreover, as commercial optimization software packages use numerical computation, the gradient calculation cost can increase, and the matrix computation process can be inefficient in terms of optimization time. Therefore, in this study, an integrated interface for efficient design optimization was developed to focus on concept design using a MODELICA language-based model. Additionally, the design variable screening by using analysis of variance, surrogate modeling through sequential design of experiments, and symbolic computation were used to solve the aforementioned problems. These were applied to the design optimization of the combat vehicle system to demonstrate the effectiveness of the integrated interface and symbolic computation. In conclusion, a concept design utilizing a MODELICA language-based model was achieved, and the optimization time achieved by symbolic computation was largely reduced in comparison to the optimization time achieved by numerical computation.

1. Introduction

As industry becomes more advanced, the use of computer aided engineering (CAE)-based design technology is increasing as product development time becomes shorter. Moreover, as computing speed increases and simulation modeling technology develops, CAE-based design technology can be used to satisfy industrial demands. The design optimization of the beam and joint of an automotive body in white [1], the design optimization of an aircraft load arm [2], and the design optimization of a ship body [3] have been carried out by private industries using CAE-based technology. Additionally, the design optimization of the mobility and firepower of an unmanned combat vehicle [4,5], design optimization of the wing of an unmanned combat aircraft [6], and design optimization of a guided missile tail [7] have been carried out in the defense industry.

The more complex a system is, the more CAE-based design optimization is required to reduce the development cost and shorten the development time. Generally, a complex system is composed of several subsystems and numerous lower level components. Moreover, the number of design variables is large, and the performance requirements are diverse. Because of these characteristics, a system level approach is required to perform the design optimization of a highly complex system. In product design, a system level approach means focusing on the system level rather than on the component level.

To carry out a system level approach, the implementation of process integration and design optimization (PIDO) software packages, which integrate multidisciplinary analyses and design processes into a single software package, is increasing. The detailed design of a high-fidelity model has been actively implemented by using commercial PIDO software packages. For example, the design optimization of a satellite separation system used iSIGHT [8], the design optimization of the morphing structure of a shape memory alloy used ModelCenter [9], the design optimization of a test reactor divertor used OPTIMUS [10], the design optimization of an automobile's torsion beam axle used PIAnO [11], and the design optimization of a panel used VisualDOC [12]. However, as CAE technology develops and the product development cycle is shortened, concept design becomes more important in reducing the development time and cost.

Concept design is the derivation of a conceptual design by a simple simulation model before carrying out detailed design. The more time

* Corresponding author.
E-mail address: thlee@hanyang.ac.kr (T.H. Lee).

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invested in concept design during the entire development process, the fewer problems may arise in the future, and the lower the overall development cost will be. However, most commercial PIDO software packages focus on detailed design using a high-fidelity model. Moreover, commercial optimization software packages have various drawbacks that originate from using numerical computation to calculate the gradient.

In this study, an integrated interface was developed with the Maple software package to focus on concept design through a MODELICA language-based model. The integrated interface consisted of design variable screening, surrogate modeling, and optimization, to enable a systematic design process. Additionally, optimization was performed efficiently by using symbolic computation to improve the conventional PIDO software packages. The usefulness of the integrated interface was described by applying it to the design of a combat vehicle system, which was composed of mobility subsystems and firepower subsystems, where each one had a large number of lower level components. Additionally, the performance requirements for the combat vehicle were diverse. Therefore, it was considered that this combat vehicle system was a suitable complex system. Moreover, the effectiveness of symbolic computation was compared in terms of optimization by symbolic and numerical computation, respectively.

This paper is organized as follows. In Section 2, the structure of the integrated interface for design optimization is described: the design variable screening, surrogate modeling, and optimization by symbolic computation. In Section 3, the target combat vehicle system is described in terms of performance requirements, design variables, and optimization problem formulation. Additionally, the design optimization process and results through the integrated interface are described. In Section 4, the contents of the paper and the conclusions drawn from the study are summarized.

2. Structure of an integrated interface for design optimization

The product development process consists of concept design, detailed design, prototyping, and mass production. CAE-based design focuses on the concept design and detailed design, as shown in Fig. 1. In the concept design stage, design changes are easy and the associated cost is low. However, in the detailed design stage, the implementation of design changes is difficult and the associated cost is high. Although detailed design has drawbacks, the general design process invests more time and makes more changes to the detailed design because of the existence of a high-fidelity model. As the high-fidelity model does not exist at the concept design stage, many designs tend to proceed to the detailed design stage. However, upfront engineering can reduce any subsequent problems by changing the design at the concept design stage using a simple simulation model that can reduce the total design cost.

Most commercial PIDO software packages focus on the conventional design process, that is, the detailed design with a high-fidelity model. In this Section, to achieve upfront engineering, an integrated interface was developed by using the Maple software package, which focuses on concept design, and a MODELICA language-based model [13]. Unlike the high-fidelity model, which uses the finite element method (FEM), the language-based model consists of principle equations. Therefore, the analysis time of the language-based model is very short and the design change is simple. The integrated interface through the language-based model consists of three components suitable to concept design, as shown in Fig. 2.

2.1. Design variable screening

As system complexity and the number of design variables increase, the optimization time also increases, and the convergence rate in the optimization decreases. Therefore, design variables with a significant influence on performance should be selected. The analysis of variance (ANOVA) is used as a method to select significant design variables. When performing ANOVA, a quartile method-based outlier analysis is implemented to handle outliers, and n-way ANOVA is developed with the Maple software package. Even if ANOVA is performed by a language-based model, results similar to those of ANOVA with a high-fidelity model can be obtained. Therefore, the efficiency of ANOVA can be improved by using a language-based model in the concept design stage.

2.1.1. Quartile method-based outlier analysis of simulation responses

In the concept design stage, a time-dependent model developed with the MapleSim software package is often used, and outliers occur because of the accumulation of repeated numerical errors in the simulation results. Meaningful ANOVA results cannot be obtained when performing ANOVA with outliers. Therefore, to obtain meaningful ANOVA results, a quartile method-based outlier analysis is used to sort out the outliers [14].

The quartile method is a method that uses the order statistics to sort out the outliers by arranging the simulation responses in the order of magnitude, as shown in Fig. 3. Before performing ANOVA, simulation analyses are performed according to a 2-level orthogonal array. Then, the median, upper quartile (Q_3), and lower quartile (Q_1), are calculated according to the simulation responses. Parameter k is set to 1.5, and the lower and upper fences are calculated by Eq. (1). If the simulation responses fall outside of the lower and upper fences, then they are sorted as outliers.

$$\text{Lower fence}=Q_1 - k*(Q_3 - Q_1)$$
$$\text{Upper fence}=Q_3 + k*(Q_3 - Q_1) \tag{1}$$

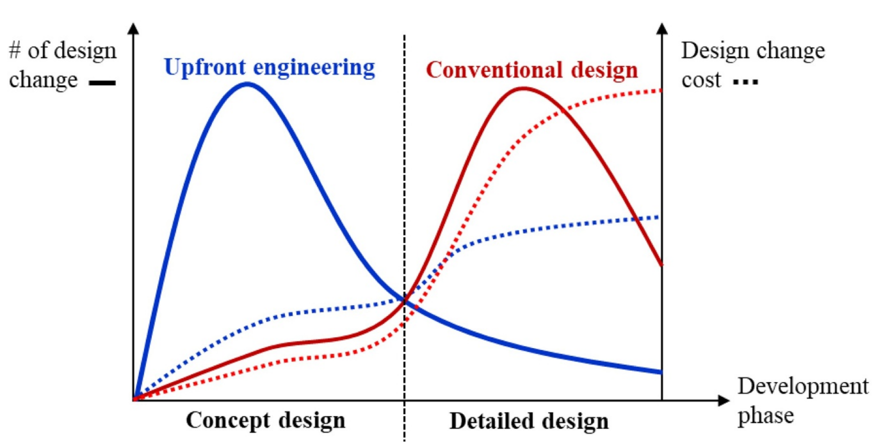

Fig. 1. Schematic of upfront engineering and conventional design.