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Variable fidelity design based surrogate and artificial bee colony algorithm for sheet metal forming process

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ABSTRACT

Optimization integrated with either one step solver (low fidelity model) or incremental nonlinear finite element solver (high fidelity model) has respectively gained increasing popularity in the design of sheet metal forming process to improve product quality and shorten lead time. However, the one step solver directly incorporated with optimization may result in inadequate design precision, while the incremental method often leads to a prohibitively low computing efficiency. In order to take the full advantages of both the one step solver and incremental solver, we present a variable fidelity algorithm which integrates the one step solver with incremental solver for optimizing sheet metal forming process in this study. In the variable fidelity method established, we need to determine the difference between the two solvers at some predefined experimental points firstly, and then constructing a corrected function using surrogate models for compensating the responses of the one step solver at other points. Different surrogate models, such as response surface methodology (RSM), Kriging (KRG), radial basis function (RBF) and support vector regression (SVR), are considered and compared for best modeling accuracy in this paper. The compensated low fidelity model can be used as a high fidelity model in the optimization process. In this study, we adopt the artificial bee colony (ABC) algorithm to obtain the global optimum. To demonstrate the capability of the variable fidelity method combined with the ABC algorithm, the optimal design of draw-bead restraining forces for an automobile inner panel is exemplified herein. The results show that the optimization with variable fidelity method presented significantly improves the computational efficiency and formability of the workpiece.
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1. Introduction

Sheet metal forming signifies an important class of manufacturing process, which has been extensively used in automotive and home appliance industries. To achieve a desirable quality with a minimum cost, traditional process design has been performed in a time-consuming and costly way [1], usually involving a series of design modifications, prototyping and try-out. As an efficient engineering tool, finite element (FE) simulation has become more and more prevalent in this context, which allows us to precisely predict a forming process by detecting such defects as wrinkling and rupture in an early stage, thereby reducing design and prototyping costs to a considerable extent. In this regard, the utilization of sheet metal forming simulations has been reported by a number of researchers. For example, Makinouchi [2] used formability analysis software to analyze four stamping parts (fenders, trunk lid outer panels, side frame outer panels and tire disk wheels) and to predict their blank geometry, springback, sheet thickness, residual stress and common defects after stamping. Panthi et al. [3] analyzed springback in sheet–metal bending using finite element analysis (FEA). Zheng et al. [4] adopted FEA to predict the location of the fracture in the sheet metal forming. Nevertheless, FEA is usually employed in a trial and error fashion and an improvement of forming processes somewhat relies on designer's experience [5]. To develop an acceptable process design, e.g. die/blank configuration and/or restraining forces, many FEA runs may be needed. However this by no means guarantees an optimum. A recent trend moving from mass production to small number production with shortening lead time to market has been becoming more and more evident, which is of a higher requirement in the design cycle [6]. These raise a strong demand in developing a more efficient and more reliable optimization procedure for the sheet metal processing design.

Various computational optimization algorithms provide us with effective tools for the above mentioned design problems [7–18]. To apply conventional mathematical programming

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methods, two demanding computing issues must be involved: finite element analysis (FEA) and sensitivity analysis [1]. For such a typical nonlinear problem as sheet metal forming with large deformation, elastoplasticity and frictional contact, the finite element analysis is typically performed by using either a one step (or namely inverse approach) [19–22] or classical incremental dynamic explicit algorithms [23]. The one step approach characterizes a much higher computing efficiency but provides only an approximate solution, which was useful mainly for preliminary design [22,24]. The incremental approach, on the other hand, typifies a better simulation precision but needs substantially higher computational cost, which is better suitable for detailed design verification [22].

As for sensitivity analysis, a path-dependent algorithm appears indispensable to obtain precise gradient information [1,6,13,25,26]. To simplify the formulation, the one step solver has been used for sensitivity analysis. For example, Batoz and coworkers [21,22] combined the one step approach with gradient based methods to optimize the blank shape and drawbead restraining forces. However, design functions involving in sheet metal forming problems are often noisy and the determination of their gradients requires substantial mathematical and computational efforts, sometimes making use of the conventional optimization methods less practicable [27]. Such computational issues force the researchers to seek more efficient and more practical approaches for the design of sheet metal forming process.

To avoid discrete or continuum finite element based sensitivity analysis, an effective alternative has been the surrogate model approach, in which the design functions are indirectly constructed through the results from the design of experiments (DOE). Its simplicity and effectiveness have drawn considerable attention recently. For example, Kok and Stander [9] adopted successive response surface method (RSM) to optimize the preforming die shape in terms of the blank weight, thereby minimizing the difference in workpiece thickness. Ohata et al. [28] employed RSM to optimize the annealing temperature and time for thickness uniformity. Chengzhi et al. [29] optimized the blankholder forces to maximize the safety zone of the forming process by using an adaptive RSM (for short, ARSM). Breitkopf et al. [30] developed a so-called moving least square RSM for achieving the uniform thickness, where the one-step solver is used in optimization procedure and the incremental solver for final verification. Jansson et al. [27] employed RSM to optimize drawbead restraining force, whose combination with a space mapping technique largely enhanced computing efficiency. Later, they further improved this in an iterative RSM [31]. More recently, Li et al. [10] developed a robust design approach by using RSM, which took into account the fluctuation of design variables. Tang et al. [16] also addressed the design of constraining force for minimizing the thickness difference subject to the constraints of failure criteria, where the one step method was adopted in constructing response functions. These work well demonstrated the effectiveness and feasibility of RSM to sheet metal forming design.

However, the existing computational optimization of the sheet metal processing has been separately using either the one step method or incremental method. In fact, these two methods are of complementary cons and pros in computational efficiency and precision [24]. It is therefore meaningful to take their full advantages for reducing the computational cost and improve numerical precision for a design solution. In addition, the success of those abovementioned sensitivity driven and surrogate model approaches largely rely on the nature of design functions formulated. Use of mathematical programming algorithms sometimes hardly guarantees a global optimum. It is therefore worthwhile attempting such "global" approaches as stochastic population based algorithms, for the design optimization [14].

In this paper, to address the aforementioned issue, a more practical procedure which integrates variable fidelity method with artificial bee colony algorithm is presented. The variable fidelity model is constructed based upon both the one step method and the incremental method. The incremental method, which requires much longer computing time, is used only at fewer experiment data points, aiming at compensating the simulation results generated by the one step method. Once the variable fidelity model is established, it will be directly used in the optimization procedure. Its fast solver allows us to explore more design points, making the optimization more reliable. To avoid utilizing mathematical programming algorithms, the population-based methods like genetic algorithm (GA), particle swarm optimization (PSO), artificial bee colony (ABC) algorithm, differential evolution algorithm and evolution strategies may be an alternative. Of those algorithms, the ABC algorithm is one of the most recently introduced population-based algorithms and the performance of ABC has been well recognized. Compared with other population-based algorithms it requires fewer control parameters. Due to its simplicity and ease of implementation, ABC has drawn considerable attention and has been successfully applied in many research areas recently [32–34]. Despite increasing awareness of the outstanding performance that the ABC algorithm offers, there has been no published work available to use it for sheet metal forming process problems to date. This paper will demonstrate the capability of the ABC algorithm incorporating with the variable fidelity method for the design of drawbead restraining forces of an automobile inner panel. The results show a significant improvement in both computing efficiency and precision for such a sophisticated practical engineering problem.

The rest of this paper is organized as follows. Section 2 proposes the variable fidelity algorithm. In Section 3, the theory of surrogate models is presented. The artificial bee colony algorithm is included in Section 4. Section 5 presents the optimization design of sheet metal forming process. Finally, the conclusion is drawn in Section 6.

2. Variable fidelity algorithm

The design optimization of a sheet metal forming process can be typically formulated as:

$$\begin{cases} \min: & F_0(\mathbf{x}) \\ s.t. \quad F_j(\mathbf{x}) \le 0, & j=1,\ldots,m \\ x_i^L \le x_i \le x_i^U, & i=1,\ldots,n \end{cases} \tag{1}$$

where $\mathbf{x}=(x^1,x^2,\ldots,x^n)^T$ denotes design variables, n is the number of design variables, $F_0(\mathbf{x})$ denotes an objective function, $F_j(\mathbf{x})$ $(j=1,\ldots,m)$ are the constraint functions, m is number of constraints, x_i^L and x_i^U are the lower and upper bounds of design variable x_i, respectively. To solve Eq. (1), the conventional optimization procedures can be mainly one of the following approaches [35,36]:

(1) *Direct coupling of the optimizer with incremental solver*: this might be most accurate without statistical fitting limitations, since the optimizer and the analysis are linked directly rather than by means of a surrogate model. However, the gradient information, computational overhead and numerical ill-conditioning often prevent this approach from being applied in sheet metal forming design practically.
(2) *Coupling of the optimizer and a statistical surrogate of an incremental solver*: in view of the drawbacks of the previous approach, a more common alternative is to couple the

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