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Optimization of sheet metal forming processes by adaptive response surface based on intelligent sampling method

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ABSTRACT

In this study, the previously developed adaptive response surface method (ARSM) is suggested for construction of metamodel for highly non-linear responses. In order to develop the accuracy and efficiency of metamodel, the particle swarm optimization intelligent sampling (PSOIS) scheme is developed. This kind of intelligent method can guarantee the sampling search in right direction and constraint the bounds of design variables in feasible region. For validation of developed method, the Rosenbrock function is successfully approximated by proposed method; corresponding metamodel appropriateness can be well predicted by analysis of variance (ANOVA). Metamodel by ARSM with PSOIS are employed for optimization of initial blank shape and blank hold force (BHF) in sheet forming process, with validations by finite element simulations using LSDYNA970 commercial code. The results show that developed method is able to produce remarkable metamodels for highly non-linear problems with multi-parameter.

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1. Introduction

In recent years, the sheet metal forming FE simulation has been studied extensively and significant developments, numerical simulation of sheet metal forming processes has become a very powerful tool in the automotive industry. Some progresses make it possible to obtain accurate and reliable results from simulation (Gelin and Ghouati, 1999; Roux et al., 1998; Stander, 2001; Kleiber et al., 2002; Zhang et al., 2002; Simpson et al., 2004; Zou et al., 2002, 2003; Wang et al., 2002). In order to prevent failures in the trial out process and reduce design cost by predicting cracking and wrinkling tendencies, FE simulation is nowadays applied to check part and die geometry at early design stage, as well as to optimize process parameters for a safe production.

Today forming simulations are mainly used in a trial and error fashion in order to develop forming processes that can produce parts with the requested properties. Since many parameters affect the result it may be difficult with this approach to find the parameters that most efficiently improve the process. Further, many different processes can be designed for the manufacturing of one part and it may be difficult and time consuming to evaluate all the design alternatives. Thus, approximation or metamodeling techniques are often used

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Abbreviations: RSM, response surface method; ARSM, adaptive response surface method; PSO, particle swarm optimization; PSOIS, particle swarm optimization intelligent sampling; FE, finite element; DOE, design of experiment; CCD, central composite design; LHD, Latin hypercube design; ANOVA, analysis of variance; RMSE, root mean square error; GA, genetic algorithm; FLC, forming limit curve; FLD, forming limit diagram; BHF, blank-holder forces.

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to model these computation-intensive processes in order to improve efficiency. Response surface methodology (RSM) is such a metamodeling method for replacing a complex model by an approximate one based on results calculated at various samples in the design space. Therefore, RSM can be used to diminish the cost of functions evaluation in structural optimization. The optimization is then performed at a lower cost over such response surfaces. Two important issues when applying RSM to a particular problem concern the design of experiments and construction of accurate functional approximations so that rapid convergence may be achieved.

RSM was well developed for physical processes by Myers and Montgomery (Myers and Montgomery, 2002) while the applications to simulation models in computational mechanics form a relatively new research field. In the late 1990s and the early 2000s, some RSMs were wildly used in sheet forming field. Roux et al. (Roux et al., 1998) discussed experimental design techniques and the regression equations for structural optimization. An application to sheet metal forming process simulated by explicit dynamics method was given by Stander (2001) with an emphasis on oscillating solutions. RSM combined with stochastic FE were used by Kleiber et al. (2002) for reliability assessment in metal forming. An original, hybrid method combining pattern search with RSM proposed by Zhang et al. (2002) used radial basis functions for representing response surfaces. In recent years, RSM based on moving least square (MLS) method was applied for construction of response formulation and implemented for optimization of sheet forming method (Breitkopf et al., 2005). A reliability–mechanical study combination of the augmented Lagrangian method and a response surface method for computing the failure probability of such a non-linear problem is suggested by Radia and El Hamib (2007). Optimal springback compensation was found by RSM in Stander (2002). In Jansson et al. (2005), space mapping was used to fit the in-draw of a complex sheet metal part. Other examples of optimization in sheet metal forming can be found in Guo et al. (2000), Abe et al. (2002), Doege and Elend (2001) and Gantar et al. (2002).

Design of experiment (DOE) is the key factor to determined accuracy and efficiency of response surface (RS) function. Due to the many differences between computer experiments and physical experiments as discussed in Simpson et al. (2004), the term "sampling" to refer to DOE is used in this paper. The sampling methods are mainly classified as four groups, including orthogonal arrays (Hedayat et al., 1999; Owen, 1992), various Latin hypercube designs (Iman and Conover, 1980; McKay et al., 1979; Park, 1994), Hammersley sequences (Kalagnanam and Diwekar, 1997; Meckesheimer et al., 2002) and uniform designs (Fang et al., 2002). The wildly used sampling (DOE) methods such as central composite design (CCD), D-optimal design and Latin hypercube design (LHD) are based on above techniques.

RSM that employs low-order polynomial functions (second-order is implemented often) can efficiently model low-order problems, and the computation of a RS model is fast and cheap. In addition, RSM facilitates the understanding of engineering problems by comparing parameter coefficients and also in the elimination of unimportant design variables. Low-order polynomial response surfaces, however, are not good for highly non-linear problems and high-dimensional problems such as sheet metal forming and crashworthiness optimization problems. It requires more samples in optimization domain to construction of accuracy RS model. Thus, the sampling methods based on statistics theories become inefficiency in highly non-linear problems in practice. Therefore, the intelligent sampling methods need to be developed to further advance the metamodeling techniques. Although the intelligent sampling methods are still new field of metamodeling, few works have been done for development. The importance sampling (IS) scheme, improved form Monte Carlo simulation (MCS), can bear the potential of improving its efficiency while maintain the same level of accuracy of MCS (Au and Beck, 1999). Zou et al. developed an indicator response surface based method, in which IS is performed in a reduced region around the limit state (Zou et al., 2002, 2003).

In this study, the previously developed ARSM (Wang et al., 2002; Wang, 2003) was applied for highly non-linear problems in practical engineering field. ARSM was developed for design optimization involving computation-intensive processes for the evaluation of objective and constraint functions, and requires a computation-intensive analysis/simulation process to evaluate these functions. As illustrated in benchmark tests in Wang et al. (2002) and Wang (2003) and the industrial design application, the ARSM can converge to a global design optimum with a modest number of function evaluations. This new method makes the global optimization of approximation based design problems feasible. In order to develop the accuracy and efficiency of metamodel, particle PSOIS scheme is developed for generation of new samples according to sampling history information. The main advantage of developed method is to guarantee the sample searching direction and reduce the bounds of constraints in feasible regions to construction RS. For validation this method, Rosenbrock function was approximated by developed method, and the model appropriateness can be well predicted by ANOVA compared with models based on LHD and central CCD. The developed optimization was employed for optimize the initial blank shape and BHF of sheet forming process successfully. The corresponding optimum results were validated by LSDYNA970 commercial code based on explicit dynamics approach. It is confirmed that highly non-linear problems with multi-parameter can be optimized successfully in remarkably accuracy by the developed optimization method.

2. Response surface methodology

2.1. *Response surface approximation*

For the most of the response surfaces, the functions for the approximations are polynomials because of simplicity, though the functions are not limited to the polynomials. For the cases of quadratic polynomials, the response surface is described as follow.

$$y = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \beta_{ij} x_i x_j \quad (1)$$

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