Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Comput. Methods Appl. Mech. Engrg. 195 (2006) 2231–2251
Computer methods in applied mechanics and engineering
www.elsevier.com/locate/cma

Perturbation-based stochastic FE analysis and robust design of inelastic deformation processes

Ioannis Doltsinis [a,*], Zhan Kang [b]

[a] *Faculty of Aerospace Engineering and Geodesy, University of Stuttgart, Pfaffenwaldring 27, D-70569 Stuttgart, Germany*
[b] *State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian 116024, PR China*

Accepted 5 May 2005

Abstract

The study addresses the perturbation-based stochastic finite element analysis and the robust design optimization of deformation processes of inelastic solids. The perturbation equations for the stochastic moment analysis of both steady-state and non-stationary processes are presented. An iteration scheme based on the secant system operator is given for the solution of the perturbation equations in case that a tangent matrix is not available. The robust design of deformation processes is stated as a two-criteria optimal design problem that attempts best mean properties of the outcome at minimum variability. The task is solved using optimization techniques based on sequential quadratic programming in conjunction with the stochastic finite element analysis. The proposed method is applied to the design of an extrusion die for robustness with respect to friction variability, and to a workpiece preform design problem. The numerical results show the potential of the method for applications regarding the design of robust deformation processes.

Keywords: Stochastic finite element method; Robust design; Inelastic deformation; Forming process optimization

1. Introduction

In a number of industrial forming processes, particularly in bulk metal forming operations such as hot extrusion and forging, elasticity has not appreciable effect on the deformation. Under this aspect an elastic material constituent can be neglected, and the deformation process is modeled as inelastic in the numerical simulation based on the viscous, viscoplastic or plastic constitutive approach to the material behaviour. Elasticity may nevertheless be of importance in determining the stress state in the solid [1].

* Corresponding author. Tel.: +49 711 6857788; fax: +49 711 6853644.
E-mail address: doltsinis@ica.uni-stuttgart.de (I. Doltsinis).

doi:10.1016/j.cma.2005.05.004

Deformation processes often involve random uncertainties in several parameters, such as loading conditions, material properties, boundary conditions, and geometrical dimensions. For instance, friction is one significant source of uncertainty in the modeling of metal forming processes. The effective friction coefficient frequently exhibits large scatter about the nominal value due to variation of the actual manufacturing conditions such as the surface roughness and the lubricant. The concerned deformation process may reflect the variability of the parameters to an extent inducing undesirable effects on the product quality. The concept of robust design, initially proposed by Taguchi, aims at reducing such a variability without eliminating the source of uncertainties by seeking a design that is less sensitive to the scatter of the system parameters.

Perturbation based stochastic finite element analysis has been extended recently to the variability analysis of forming processes. Sluzalec [2], and Grzywinski and Sluzalec [3] presented stochastic finite element analysis of rigid-viscoplastic and rigid-thermo-viscoplastic deformation. The authors adopt the second-order perturbation technique for the incorporation of system uncertainties into the finite element equations. However, the perturbation equations are derived based on linearized matrix expressions in which the implicit dependence of the system matrix upon the velocity field is neglected. Doltsinis [4] presented a theoretical formulation of perturbation based stochastic analysis for deformation processes of viscous solids. Thereby, both the geometry and other random variables at the current instant are considered as random input, which enables the formalism to account consistently for random variables evolving during the course of the deformation.

In engineering practice, a variety of requirements may be imposed on the design of deformation processes of solids. For example, an important issue in the design of an extrusion die is the pressure distribution in the workpiece material. In a different task, the preform design, the initial shape of the workpiece material is to be determined in such a way that a final product with the desired material state and geometry is achieved [5,1]. Conventional process design techniques usually employ trial-and-error procedures or approaches based on the Design of Experiments (DOE), such as Taguchi's robust design methodology. The developed state of computer process simulation and of engineering optimization enables cost effective conception of industrial forming processes by computer aided design.

In the literature, much work is reported on the optimal design of forming processes, but rarely addressing non-deterministic optimization. Studies on process design in metal forming under deterministic assumptions can be found in the papers by Byon and Hwang [6], Badrinarayanan and Zabaras [7], Antonio and Dourado [8], Doltsinis and Rodic [9]. Non-deterministic design optimization has been employed by Kok and Stander [10] for the optimal design of a sheet metal forming process.

Methods of analysis and design for deformation processes with randomness have been exposed in a previous publication [4] from a general point of view considering the suitability of the statistical Monte Carlo technique and the non-statistical perturbation approach for the treatment of particular tasks in design space exploration and design improvement. The present account focuses on the development of the perturbation technique to an analysis tool and its employment for process design in conjunction with numerical optimization algorithms. In this connection, related experience in the field of linear and nonlinear structures [15–17] appeared advantageous.

In the present study, the perturbation equations for the first-order approximate mean and variance of the process state variables (velocity and geometry) are presented on full account of the nonlinearity of the problem, for both steady-state and non-stationary conditions. An iteration scheme is given for the solution of the perturbation equations using the secant operator of the system instead of the tangent matrix. The robust design of the forming process is stated as a multi-criteria optimal design problem and is solved using available optimization software based on sequential quadratic programming (SQP) in conjunction with the stochastic moment analysis. For this purpose, both the mean value and the standard deviation of the objective function for the outcome are requested to attain minimum values. The above two requirements, frequently conflicting, are compromised by introducing a compound desirability function which allows accounting for preferences in the particular design. Details are given in [4,15]. To illustrate the applicability of the proposed