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Development of parallel 3D RKPM meshless bulk forming simulation system

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Abstract

A parallel computational implementation of modern meshless system is presented for explicit for 3D bulk forming simulation problems. The system is implemented by reproducing kernel particle method. Aspects of a coarse grain parallel paradigm—domain decompose method—are detailed for a Lagrangian formulation using model partitioning. Integration cells are uniquely assigned on each process element and particles are overlap in boundary zones. Partitioning scheme multilevel recursive spectrum bisection approach is applied. The parallel contact search algorithm is also presented. Explicit message passing interface statements are used for all communication among partitions on different processors. The parallel 3D system is developed and implemented into 3D bulk metal forming problems, and the simulation results demonstrated the efficiency of the developed parallel reproducing kernel particle method system.

Keywords: Parallel; Reproducing kernel particle method; Bulk forming; Domain decomposition method; Partition; Message passing interface; Speedup

1. Introduction

The non-linear finite element formulations for non-linearity of geometric and material have been well developed and a lot of significant works have been completed in bulk forming analysis. Nevertheless, FEMs are still ineffective in dealing with some extreme material distortions owing to severe mesh distortion. There are difficulties in solving problems involving large deflections and moving discontinuities. Typical problems include extremely large deformations in manufacturing processes, the propagation of interface between solids and liquids in casting, the propagation of cracks with arbitrary and complex paths in failure, and the tracking of the growth of phase boundaries and microcracking in advanced materials development. Some of FEMs require remeshing models in large deformation conditions; it still requires considerable computational efforts. Meshless methods eliminate mesh distortion for both large shape design changes and large deformation non-linear analysis.

A variety of meshless modeling methods have recently emerged [1]. RKPM was proposed by Liu et al. [1–5,39] to improve the accuracy of the SPH [27–29,31,32] method for finite domain problems. These methods have advantages over traditional FEMs for their ability to handle large deformation problems without mesh distortion, and for their solution accuracy due to the large domain of influence covered by particles/nodes. In this method, the kernel function is modified by introducing a correction function to meet the reproducing conditions. The resulting modified kernel function exactly reproduces polynomials to a specific order and thereby fulfills the completeness requirement. The shape functions developed from the method were later

Abbreviations: RKPM, reproducing kernel particle method; EFG, element free Galerkin method; PIM, point interpolation method; SPH, smoothed particle hydrodynamics; FEM, finite element method; RSB, recursive spectrum bisection; MRSB, multilevel recursive spectrum bisection; DDM, domain decomposition method; MPI, message passing interface; EBC, essential boundary condition; SYMMLQ, sparse symmetric equations; PE, process element.

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proven to be equivalent to moving least-squares kernel interpolates if linear basis functions were used [1–3]. Liu et al. also introduced wavelets [5] as the kernel functions and successfully applied RKPM to multiple scale analysis.

More recently, some effort has also been devoted to the solution of bulk metal forming processes by means of meshless approaches. Referenced papers encompass the following operations: ring compression [6,7], upsetting [6–13] and extrusion [6,7,10,14,15].

Meshless methods encounter the major technical barrier-low computation efficiency. Because meshless methods are based on the high order interpolation, the computation time of meshless requires much longer than FEMs. By taking a general view to the content of these papers it appears that major results are generally limited to 2D problems and simple 3D problems. Therefore, meshless methods are not wildly applied in practice. Parallelization of meshless codes is the way to settle expense of meshless computations. The parallel meshless methods to decompose the domain into several subdomains to solve are called DDM. DDMs are useful in two contexts. First, the division of problems into smaller problems through usually artificial subdivisions of the domain is a means for introducing parallelism into a problem. In this manner, problems that are intractable on serial computers can be solved on parallel computers. Second, many problems involve more than one mathematical model, each posed on a different domain, so that domain decomposition occurs naturally. DDMs are wildly used for explicit FEM problems [42,43,45]. It is natural that DDMs [44] can advance the meshless computation efficiency easily.

The present treatment will focus on the RKPM for explicit dynamic analysis of bulk metal forming problems, but the procedures can directly apply to some other meshless methods (e.g. EFG [1,30], PIM [16]) without difficulties. Several distinct advantages of RKPM are its ability to accurately model extremely large deformations without mesh distortion problems and its ease to adaptive modeling by simply changing particle definitions for desired refinement regions.

In this paper, an overview of a Lagrangian RKPM for non-linear explicit dynamic analysis is first given. A general description of the parallel implementation is described. The parallel procedure primarily consists of a mesh partitioning pre-analysis phase, a parallel analysis phase that includes explicit message passing among partitions on separate processors. In the finial, the numerical examples have been presented to demonstrate the efficient parallel 3D RKPM system.

2. Weak form and discretization of RKPM for contact problems

The reproducing kernel approximation [1–5] of a function $u(X)$ in a domain Ω_x is expressed

$$u^a(X) = \int_{\Omega x} \Phi_a(X - Y)u(Y)\mathrm{d}\Omega_x, \tag{1}$$

where $u^a(X)$ is the reproduced of function $u(X)$, and Φ_a is the window or kernel function with compact support.

In the following X represents the material coordinates, x is the spatial coordinate and u is the displacement of the particles and t denotes the time.

Discretizing the domain Ω_x by a set of particles $\{X_1, X_2, \ldots, X_{\mathrm{NP}}\}$, where NP is the total number of particles, the integral is approximated by the following summation:

$$u(X,t) = \sum_{I=1}^{\mathrm{NP}} N_I(X)u_I(t), \tag{2}$$

where $N_I(X)$ is the Lagrangian shape function defined by

$$N_I(X) = C(X; X - X_I)\Phi_a(X - X_I)\Delta V_I. \tag{3}$$

$C(X; X - X_I)$ is the correction function and ΔV_I is the volume of particle I. The more details on the construction of the shape function of RKPM can be found in Refs. [1–5].

For an approximation with the virtual work principle, the essential boundary conditions (EBCs) must be satisfied directly by the interpolation functions or accommodated by augmenting the variational statement with constraints. A major difference between RKPM and other methods (e.g. FEMs) is the manner in which EBCs can be enforced directly. The non-local interpolation condition of equation poses an additional computational challenge. Whereas EBCs for finite elements are imposed locally at particles (because they possess the Kronecker delta property), The EBCs enforcement with RKPM are non-local over a patch of particles/nodes. In some cases, the EBCs can be adequately approximated by local specification at the particles (assuming a Kronecker delta property). This approximation can be accurate, by St. Venant's Principle, when the primary regions of interest are away from the EBCs. In general, however, a coupled set of equations is usually solved, even for explicit analyses. Previous efforts used Lagrange multipliers to constrain the variational statement [17] or a set of simultaneous equations is directly solved. In either case, significant computations were generally necessary to enforce the EBCs. These procedures also are not well suited for parallel processing, since they must generally be made over multiple processors.

Kent [18] proposes an alternate approach that may also require significant computational effort, as it is algebraically equivalent to other existing equations solving methods. By treating the imposition as a transformation of the interpolation functions, however, this form is better for parallel processing. Describing the EBC equations by

$$g_B = \sum_{J=1}^{\mathrm{NP}} N_J(X_B)u_J, \tag{4}$$