Optimized Meshless Algorithms for Seamless Integration of CAD, Simulation, and Design

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Abstract

The conventional finite element methods have intrinsic difficulty in solving problems involving moving discontinuities, large material distortion, multiple-scale phenomenon, and high gradients due to the regularity requirement of the grid based finite element method. There is also a major bottleneck in the integration of CAD, analysis, and design using the conventional finite element methods. Meshfree method is a new generation of computational method that offers an alternative way of solving PDEs without the burden of a mesh. Under this OPAAL program, several new and improved meshfree formulations and numerical algorithms have been developed to address the aforementioned difficulties in the finite element methods and to tackle the applicability of meshfree method to realistic engineering and scientific problems.

Summary

The major contributions of meshfree method development are summarized as follows:

1. Enhanced meshfree method for a direct imposition of essential boundary conditions:
   Meshfree approximation functions generally do not possess Kronecker properties, and this leads to complications in the imposition of essential boundary conditions. Under OPAAL program, several methods have been proposed for a direct imposition of essential boundary conditions in meshfree computation. This includes the development of a mixed transformation method, a boundary singular kernel method, and the construction of a reproducing kernel interpolation function that recovers Kronecker delta properties in the meshfree approximation. These methods reduce meshfree computation about 50-70%.

2. A stabilized nodal integration method for domain integration of weak form:
   The major disadvantage of meshfree method is its high computational cost. One major cause of the high CPU is due to the use of higher order Gauss quadrature rules in the domain integration of weak form. In this research, a stabilized conforming nodal integration (SCNI) method has been developed to substantially accelerate meshfree computation without sacrificing accuracy and convergent rate. In fact, since the proposed SCNI meets integration constraints and linear exactness in the Galerkin approximation, in most cases SCNI provides better solution accuracy and higher convergent rate than the meshfree solution obtained by the Gauss integration method. This development also eliminates the need of a background grid in meshfree analysis.

3. A meshfree smooth contact formulation for multi-body contact:
   Many engineering applications, such as manufacturing processes, involve complex multi-body contact conditions. Conventional finite element contact formulation often encounters iteration convergence difficulties in the numerical iteration process of contact computation due to the use of C0 approximation of the contact surface. Further, contact problems usually accompany localized large material deformation that often leads to mesh distortion and solution divergence in the finite element contact analysis. In this research, a meshfree

approximation of contact surface geometry and contact kinematics using smooth functions has been proposed. This formulation effectively resolves iteration convergence difficulty in problems involving large sliding contact. Due to the use of meshfree approximation, mesh distortion obstacles in the finite element contact analysis have also been eliminated.

4. Progressive adaptivity meshfree formulation for large deformation and contact analysis:
   The naturally conforming property of meshfree approximation is an attractive feature for adaptivity analysis. In meshfree adaptivity formulation, particles can be added or deleted in the domain of interest without dealing with compatibility issues in the finite element method. The development of meshfree adaptivity formation in this research contains two parts. The first is an error indicator based on a reproducing kernel filtering concept. In this approach, the output of the low-pass filter is a projection of numerical solution onto a space spanned by the basis functions in the reproducing kernel approximation. The output of the high-pass filter represents the difference of the numerical solution and the output of the low-pass filter, thus representing higher order components of the numerical solution. This two-scale decomposition of the numerical solution has been used for indication of errors in the meshfree solution. The second part of this work is the development of numerical algorithms and state/field variable transfer methods for progressive adaptivity computation. The field variables are transferred to the newly added particles using reproducing kernel approximation functions. The state variables are transferred using a two-step approach that ensures the satisfaction of consistency conditions in the material laws.

5. Seamless integration of CAD, analysis, and design
   Without a mesh for domain discretization and approximation of unknown variables, the integration of CAD geometry representation, analysis, and design optimization can be performed more directly and effectively. (This part requires everyone’s contribution)