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Inverse adaptation of a Hex-dominant mesh for large deformation finite element analysis

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Abstract

In the finite element analysis of metal forming processes, many mesh elements are usually deformed severely in the later stage of the analysis because of the corresponding large deformation of the geometry. Such highly distorted elements are undesirable in finite element analysis because they introduce error into the analysis results, and, in the worst case, inverted elements can cause the analysis to terminate prematurely. This paper proposes a new inverse-adaptation method that reduces or eliminates the number of inverted mesh elements created in the later stage of finite element analysis, thereby lessening the chances of early termination and improving the accuracy of the analysis results. By this method, a simple uniform mesh is created initially, and a pre-analysis is run in order to observe the deformation behavior of the elements. Next, an input hex-dominant mesh is generated in which each element is "inversely adapted", or pre-deformed in such a way that it has approximately the opposite shape of the final shape that normal analysis would deform it into. Thus, when finite element analysis is performed, the analysis starts with an input mesh of inversely adapted elements whose shapes are not ideal. As the analysis continues, the element shape quality improves to almost ideal, and then, toward the final stage of analysis, degrades again, but much less than would be the case without the inverse adaptation. This method permits the analysis to run to the end, or to a further stage, with no inverted elements. Besides its pre-skewing the element shape, the proposed method is also capable of controlling the element size according to the equivalent plastic strain information collected from the pre-analysis. The proposed inverse adaptation can be repeated iteratively until reaching the final stage of deformation.

Keywords: Large deformation; Metal forming simulation; Inverse adaptation; Mesh adaption; Bubble mesh

1. Introduction

The simulation of metal forming processes is one of the most common applications of large-deformation finite element analysis. In metal forming, the blank is stamped or punched and thus undergoes a drastic change in shape. In the simulation of this process, as the blank is reshaped the mesh elements of the blank are deformed, and element shape quality decays as analysis continues. At later stages of the analysis, elements can become severely distorted or inverted causing inaccurate results, slow convergence, and premature analysis termination. An example of such large-deformation analysis is illustrated in Fig. 1. This is a three-dimensional forming example, containing a punch that deforms a blank into a geometry with high-curvature corners. In the later stage of analysis several elements become severely distorted and inverted.

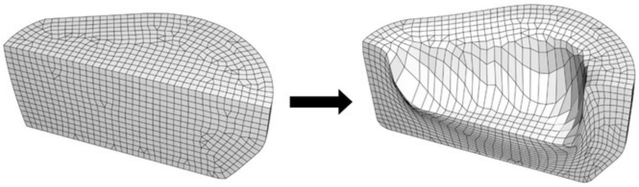

Fig. 1. An example of large-deformation finite element analysis.

In light of this problem, this paper proposes a new "inverse adaptation" approach to reduce the number of ill-shaped elements at the end of the analysis. The term "inverse adaptation" is used to illustrate the concept of this method, in which we first predict the way each mesh element will be deformed during simulation, and then create a new input mesh by pre-deforming the elements so that they have approximately

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the opposite shapes of those predicted. Unlike conventional methods, which start with a mesh of ideal elements that become severely distorted over the course of analysis, the proposed method starts with a mesh of slightly distorted elements whose quality reaches ideal as the analysis continues, and then degrades again in the final stage. This new method better distributes error across the life of the analysis and thus improves the accuracy of the results, reducing the need for remeshing and thereby improving computational cost, and lengthens the life of the analysis by avoiding early termination.

Similar methods for two-dimensional quadrilateral and three-dimensional tetrahedral meshes have been proposed earlier, and it has been proved that inverse adaptation can successfully extend the life of the analysis as well as reduce the number of ill-shaped elements at the later stage [4–6]. This paper proposes a method of inverse adaptation based on a similar, but extended concept to generate a hex-dominant mesh. The major difference between the adaptation method presented in this paper and the previous ones is the node mapping technique. In addition, due to the complexity of the analysis, the three-dimensional adaptation is applied iteratively in order to reach the final stage of deformation, while this is not necessary in two-dimensional adaptation. Details can be found in Section 3.

Currently, there are two techniques commonly used to address the problem of severely distorted elements in large-deformation finite element analysis: adaptive remeshing, and Arbitrary Lagrangian–Eulerian (ALE). Adaptive remeshing replaces a severely distorted mesh with a well-shaped mesh every certain number of steps in the analysis. In the analysis of a complicated geometry, however, frequent remeshing is necessary, which raises the computational cost significantly. The other technique, ALE, is a type of analysis reference frame developed to reduce the repetition of complete remeshing. In ALE, the mesh is not connected to the material; therefore, mesh elements do not suffer the severe deformation that the material undergoes. However, the complexity of this method, especially in solving the control equations and variable mapping processes, is a drawback in contrast to a pure Lagrangian analysis reference frame.

The purpose of the inverse-adaptation method proposed here is not to provide a replacement of the two existing techniques. Adaptive remeshing may still be required on complex geometries even when using the proposed inverse-adaptation method, but it does not become necessary until later in the analysis; furthermore, the repetition of adaptive remeshing required during simulation is significantly reduced, improving computational cost and reducing computational errors. Moreover, because all the work is done in Lagrangian analysis, we can avoid the complications of equation solving and variable mapping of ALE analysis. If desired, the proposed inverse-adaptation method can also be used for any analysis performed by the ALE method.

The remainder of the paper is organized as follows: Section 2 discusses the details of the two existing methods used in large deformation finite element analysis: adaptive remeshing and ALE. Section 3 discusses the proposed inverse-adaptation method for a hex-dominant mesh. Results are shown in Sections 4 and 5 is the Conclusion.

2. Previous methods

2.1. Adaptive remeshing

Adaptive remeshing is a technique for replacing an existing mesh with a new mesh when the element quality of the existing mesh is no longer sufficient for the analysis due to severe distortion. A typical remeshing process includes the following procedures: determining the error estimator to define the remeshing criteria, generating a new mesh, and transferring the history-dependent variables from the old mesh to the new mesh [21,11]. Most common remeshing criteria are mesh discretization errors based on strain errors in the L_2 norm [8,9,11,15,21,25,26], element distortion errors based on element shape quality [8–10,13,14], and geometric interference errors [8,13,14]. Most remeshing algorithms are developed to apply automatic mesh generation techniques to completely remesh the entire domain of the workpiece [3,13,14]. And because the newly created mesh may not necessarily have the same topology as the original mesh, and the number of nodes and elements of the new mesh may differ from the original mesh, the state variables and history-dependent variables must also be transferred from the original to the new mesh. State variables include nodal displacements and variables of the contact algorithm. History dependent variables include the stress tensor, strain tensor, plastic strain tensor, etc.

The remeshing process is usually repeated many times during the analysis in order to replace the highly distorted mesh by a newly better quality mesh, which consequently reduces the discretization errors. Nevertheless, there are several important requirements for a good adaptive remeshing technique, namely, edge detection, contact/penetration checking, volume difference checking, and parameter adaptation. The contact/penetration checking is a very time consuming operation, and numerical methods and heuristic assumptions are usually applied; this can lead to errors in the analysis result. Volume difference checking is also crucial for some cases, because multiple remeshings can cause a loss of volume which is not acceptable for industrial applications [12].

Additionally, when the entire domain needs to be remeshed and frequent remeshing is necessary, the computational cost increases significantly. Typical metal forming simulations need between 20 and 100 complete remeshings during finite element analysis [12]. To reduce the computational cost, several methods are developed using error estimators and the h-adaptive process to apply remeshing locally to only a limited number of elements [21,25,26]. Nonetheless, the process to map the state variables from the old mesh to the new mesh in adaptive remeshing method usually induces significant loss of accuracy, especially when frequent remeshing is essential. Therefore, methods to reduce the number of complete remeshings during the simulation are worthwhile, because they would consequently produce a more accurate analysis result.

The inverse-adaptation method presented in this paper delays the occurrence of ill-shaped elements and lets the