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Why the Boundary Face Method is a truely isogeometric method

Jianming Zhang

ABSTRACT. Within a successful CAE driven product development, there are two fundamental issues: a seamless interaction between the CAD and CAE packages and a fast solver for very large scale computation. The first issue is associated with the discretization of any complexly shaped domain into elements for a mesh-based method, such as the Finite Element Method (FEM) or Boundary Element Method (BEM). In the best case modifications in the CAD model can be transferred to the CAE model and vice versa. The second issue is inevitable for a daily design process, as a complete simulation chain for practical problems usually involves very large scale computations and can be very long.

In the mesh-based methods, the task of mesh generation for complex geometries is often time-consuming and prone to errors, and the difficulties with re-meshing in problems involving moving boundaries, large deformations or crack propagation is crucial. For this reason, any improvements or speedups in the meshing procedure are of great industrial interest. A major step towards achieving this goal was presented in the paper by Hughes et al. (2005) introducing the idea of isogeometric analysis [1]. In the isogeometric analysis method, basis functions generated from NURBS (Non-Uniform Rational B-Splines), a standard technology in CAD systems, are employed to construct an exact geometric model and represent field variables, such as displacement, temperature, etc. A distinct advantage of isogeometric method over other mesh-based methods is that ‘NURBS elements’ exactly represent the geometry and subsequent refinement does not require any further communication with the CAD system. Before constructing a mesh of ‘NURBS elements’, one should match the exact CAD geometry by NURBS surfaces (see Fig. 1). However, most industrial products can be geometrically described by surfaces in simplex shapes, such as planar, cylindrical, spherical and toroidal surfaces, etc. These surfaces are simply expressed by analytical functions and already available in all CAD packages. Converting the simplex surfaces into NURBS ones is neither convenient nor efficient. It is obviously unreasonable to force the CAD providers to change their format to meet CAE requirements. On the other hand, dealing with the gaps between adjacent NURBS faces is still kept an obstinate difficulty, especially in 3D cases.

Based on a combination of the computer graphics and boundary integral equation (BIE) [2], a boundary face method (BFM) is proposed by Zhang et al. (2009) [3]. The BFM is a truely isogeometric method, as both boundary integration and variable approximation are performed on the boundary faces of a solid, which are represented in parametric form exactly as the boundary representation (B-rep) data structure in most CAD systems. The parametric surface, which encapsulates the exact geometry of corresponding face, is discretized by surface elements in parametric space (see Fig. 2). These elements are used for the boundary integration and variable approximation. For boundary integration, however, the geometric data at Gaussian quadrature points, such as the coordinates, the Jacobian and the outward normal are calculated directly from the faces rather than elements, thus no geometric error will be introduced. Moreover, as the BFM is implemented directly on the B-rep of CAD systems, it should be possible to exploit their Open Architecture feature, and automatically obtain required coefficients (representation). Therefore, this implementation has a real potential to seamlessly interact with CAD software, integrating easily geometric design and engineering analysis into a completely unified framework.

For the second issue, several methods that dramatically reduce memory and computational cost have been developed in the last two decades. In this work, we adopt a Geometric cross approximation (GCA) method [4], which is equivalent to the Adaptive Cross Approximation (ACA) but without iteration, to accelerate the BFM computation. To apply the fast BFM to simulations for practical problems, a primary version of Complete Solid Stress Analysis (CSSA) software (Potent 1.0) has been developed based on the interface of UG-NX (see Fig. 3). So far, the Potent 1.0 is able to solve problems in theories of steady state and transient heat transfer (see Fig. 4), static elasticity (see Fig. 5) and acoustics (see Fig. 6) and problems with arbitrary complex structures (see Fig. 7) [5-9]. Details can be found at the website: **http://www.5aCAE.com**. The Potent 1.0 exhibits the following advantageous features: (1) **Automatic** meshing and analysis for complicated structures with complex geometries; (2) **Accuracy** much better than existing

FEM tools, to ten digits or more, is achievable and able to capture local stress concentration at any small sized features of a structure; (3) **Arbitrary** geometries and material compositions of structures can be easily handled by seamless interaction with CAD packages; (4) **Accelerated** by the fast methods, such as the Fast Multiple Method, the Hierarchical Matrix and the Adaptive Cross Approximation, thus able to perform large-scale computation within due time; (5) **Adaptive** solution procedures to guarantee the reliability of the computational results. The success of the integration of fast BFM and UG-NX demonstrate that it may be an important step toward automatic simulation.

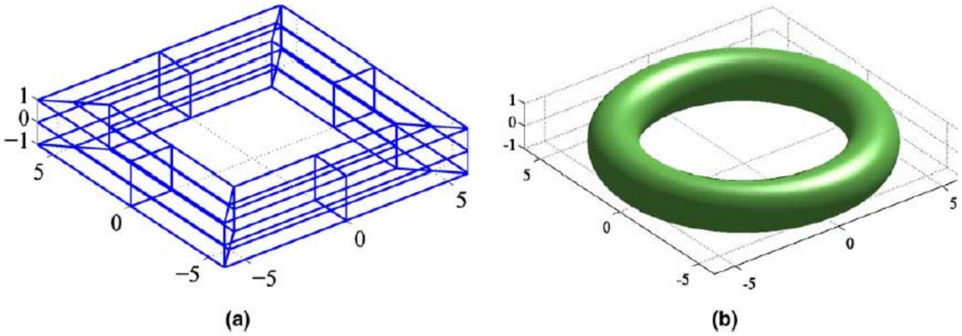


Figure 1. NURBS surface description of a torus: (a) Control net for toroidal surface; (b) toroidal surface.

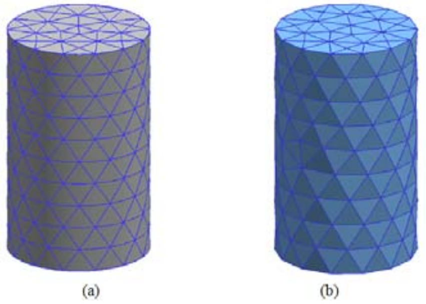


Figure 2. Two types of boundary discretizations. (a) BFM elements; (b) BEM elements.

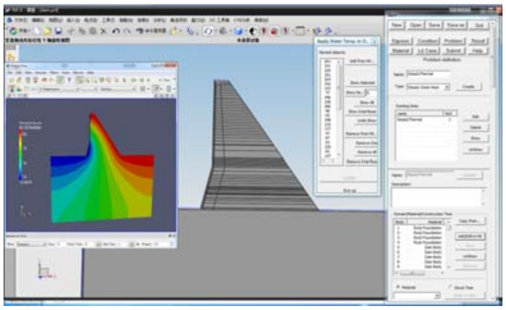
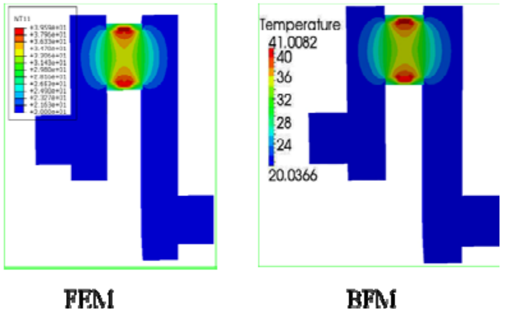
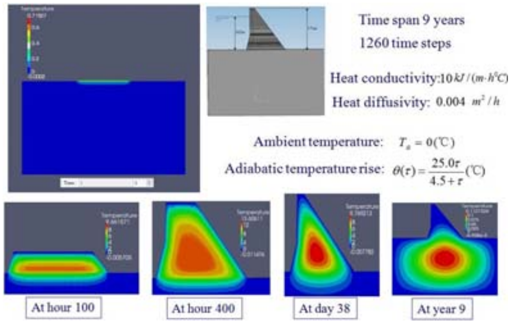


Figure 3. UI of the Potent 1.0.

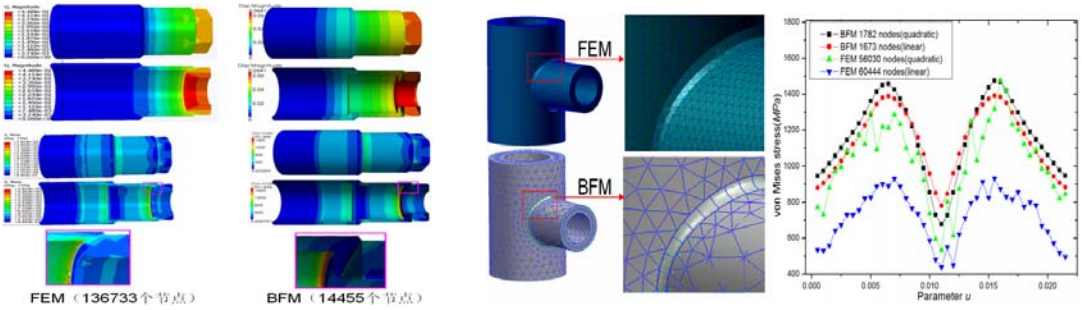


(a)



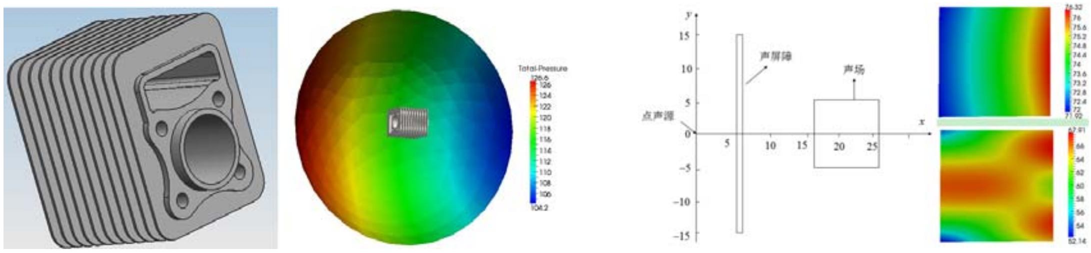
(b)

Figure 4. Heat transfer analysis: (a) analysis of steady temperature field of engine crankshaft; (b) analysis of transient temperature field of dam construction process.



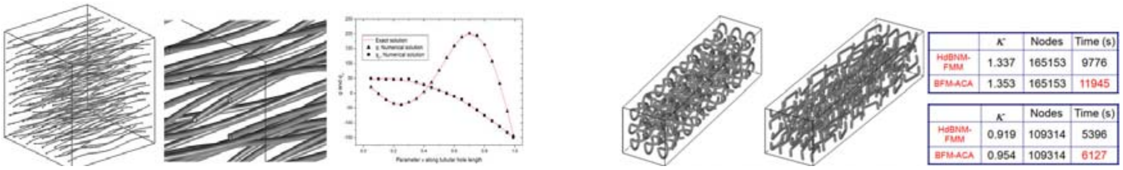
(a) (b)

Figure 5. Static elasticity analysis: (a) Stress analysis of nozzle cap nut of engine; (b) Stress analysis of manifold with fillet.



(a) (b)

Figure 6. Acoustic problem analysis: (a) acoustic radiation analysis of a complex structure; (b) acoustic filed analysis of a noise barrier of freeway.



	K	Nodes	Time (s)
HdBNM-FMM	1.337	165153	9776
BFM-ACA	1.353	165153	11945

	K	Nodes	Time (s)
HdBNM-FMM	0.919	109314	5396
BFM-ACA	0.954	109314	6127

(a) (b)

Figure 7. Analysis of complex structures: (a) steady-state heat conduction analysis of a block with a large number of tubular holes; (b) carbon nanotubes (CNT) composite simulation.

Keywords: Isogeometric analysis, Boundary face method, Complete solid stress analysis, Geometric cross approximation.

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State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, College of Mechanical and Vehicle Engineering, Hunan University, Changsha 410082, China
E-mail address: **zhangjm@hnu.edu.cn**