Historical development and future prospects of cross integration of computational mechanics and computational geometry

In industry the standard output of geometrical modeling in computer aided design (CAD) is a non-uniform rational B-Splines (NURBS) based B-Rep model, especially for free-form geometries. The predominant method used in the industry for solving structural problems is classical finite element analysis (FEA). This method typically uses linear respectively quadratic polynomials defined over non-overlapping subdomains (the elements) for geometry representation. Thus, for standard design-through-analysis workflow, a complex geometry transformation called meshing is necessary. The analysis is usually performed using a computer aided engineering (CAE) system. Although the geometric transformation can be easily achieved for many applications in solid mechanics, it constitutes a severe bottleneck for structures of highly complex geometry. In such occasions, the process is computationally very expensive, is hard to fully automate, and often leads to error-prone meshes, which have to be improved manually by the user. The transformation task is now estimated to take over 80% of the overall analysis time, and engineering designs are becoming increasingly complex (see Fig 1). Therefore, both design oriented and analysis oriented communities in engineering are urgently expecting for seamless integration between CAD and CAE, which is essentially crosses and integration between computational mechanics and computational geometry.

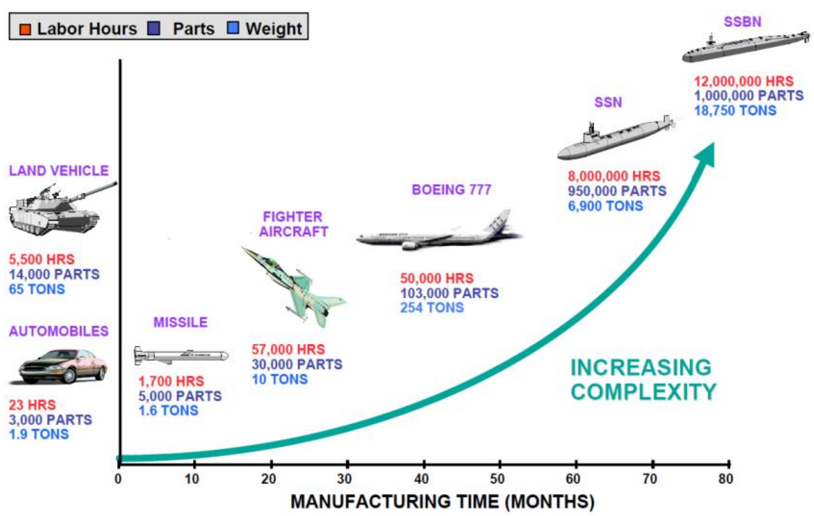

Fig 1. Engineering designs are becoming increasingly complex, making analysis a time consuming and expensive endeavor. (Courtesy of General Dynamics / Electric Boat Corporation)

The first crosses and integration between computational mechanics and computational geometry happened when the concept of isoparametric analysis was proposed in the 1960s. Isoparametric elements are adopted in most commercial codes now. After Non-Uniform Rational B-Splines (NURBS) was proposed in the 1980s, computer aided design (CAD) developed fast and became a new independent subject. Then design and analysis gradually became independent, and a new cross research field named mesh generation was born. The discussions on the importance of integrating modeling and computation began at the beginning of their moving toward independence, although it essentially had just a limited influence on engineering practice until the concept of isogeometric analysis (IGA) was proposed in 2005. Seamless integration between CAD and CAE has now become one of the core issues that need to be addressed in advanced manufacture. The developmental level of advanced manufacture is an important indicator of core competitiveness of a country. Thus, IGA initiated a new wave of research and, within just 12 years, introduced a vast variety of results, opening a new view on future concepts for design and simulation. The IGA concept comes from isoparametric analysis. It heralds a second wave of deep crosses and integration between computational mechanics and computational geometry.

Modern industry develops for higher, faster and more refined directions. The accompanied computational solid mechanics presents high accuracy, self-adaptiveness, high efficiency, strong non-linearity, and multi-scale phenomena. The conventional low-order schemes of finite element method met with difficulties in dealing with such problems. The high-order schemes have to be adopted, which requires high-order meshes that raise new requirements on the crosses and integration between computational mechanics and computational geometry. Our research integrated the fundamental theories of computational mechanics and computational geometry and proposed the Non-Uniform Rational Lagrange (NURL) functions, so that both theories can use the same bases functions. Based on this work and our work on high-order schemes earlier, we got the support of National Natural Science Fund and external sources of project-based funding to develop software that seamlessly integrates CAD and CAE (Fig 2). The information required in the process of mesh generation is adequately considered and retained in the process of geometric modelling in our codes, including the information needed in high-order mesh generation. Thus, deep crosses and integration between computational mechanics and computational geometry can be accomplished.

With the support of another project funded by the NSFC, we integrated analytical and numerical method and proposed the differential quadrature hierarchical finite element method (DQHFEM). We solve the numerical stability and computational efficiency problem of high-order schemes, the problem having been confusing the computational mechanics circles since the proposal of the finite element method. On this basis, we further solve the problem of high-order mesh generation by integrating with IGA. The DQHFEM only needs to generate meshes once, which greatly simplifies the bottle neck problem of pre-process that restricted the application of FEM. The DQHFEM integrated with the seamless integration of CAD and CAE technologies can accomplish high accuracy, self-adaptiveness, high efficiency, strong non-linearity, and multi-scale analyses. The high accuracy (Fig 3) and self-adaptive capabilities of the DQHFEM have advantages in frontier research such as attitude control simulation of space telescope (needs accuracy about 8 significant digits) and 3D printing simulation (needs self-adaptiveness). The DQHFEM is not sensitive with mesh distortion (Fig 4), and can reach much higher accuracy (Fig 5) using much less degrees of freedom (DOFs), which are important in multi-scale (has singularities) and strong non-linearity (needs a lot of iterations) simulations.

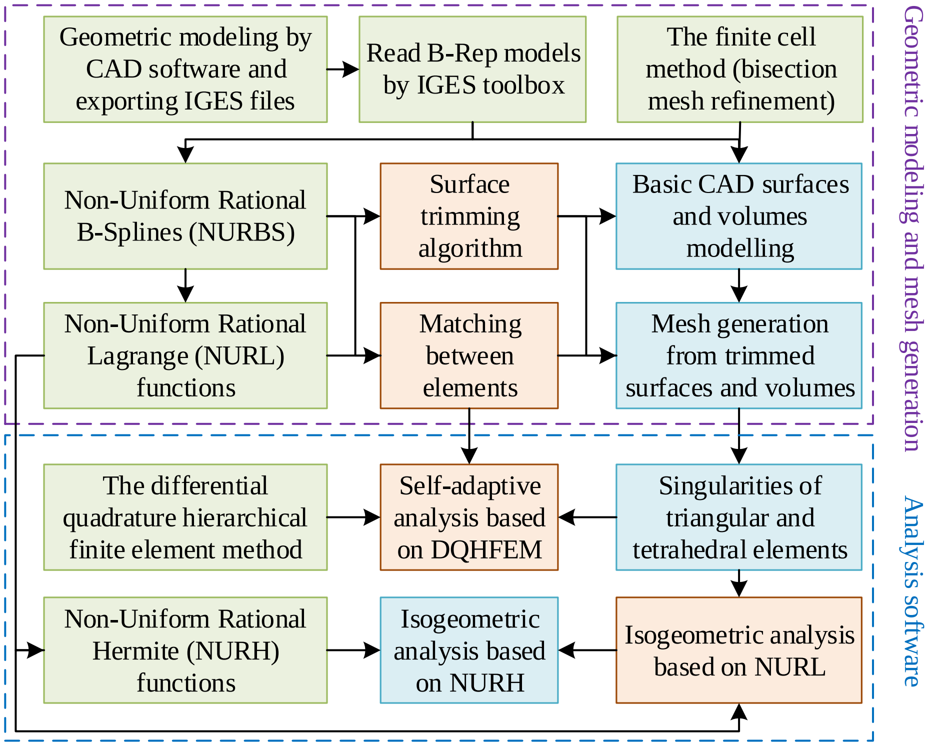

Fig 2. Flow chart of seamless integrated CAD-CAE software development

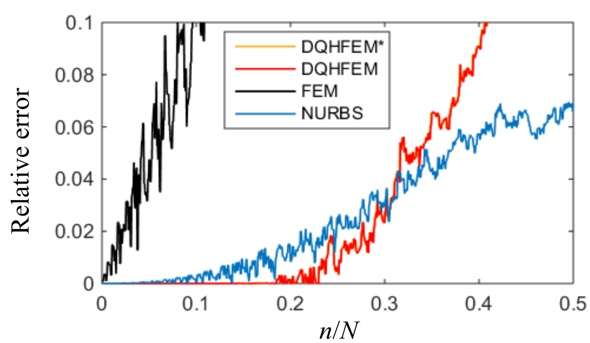

Fig 3. Simply supported plate. Relative error of discrete spectra using the differential quadrature hierarchical finite element method (DQHFEM), FEM and NURBS.

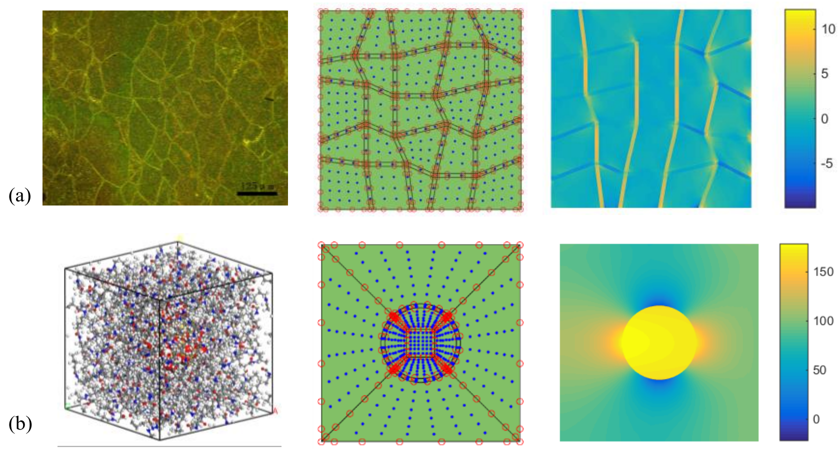

Fig 4. DQHFEM analysis of metallographic structure of TC18 Titanium alloy (a) and polymer-nanoparticle composites (b). The DQHFEM provides correct results with difference of magnitudes between interface scale and matrix/particle scale.

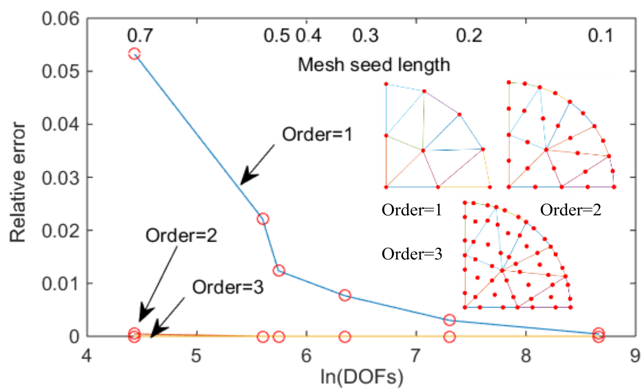

Fig 5. The accuracy of linear elements with 5000 ($e^{8.6}$) degrees of freedom (DOFs) cannot reach the accuracy or our quadratic and cubic elements with less than 100 ($e^{4.5}$) DOFs.

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References

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