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An introduction to 5aCAE software based on DiBFM: CAD/CAE integration, dual interpolation, exact geometry and non-conforming mesh

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ABSTRACT

CAE/CAD integration has always been the focus of competition among CAE software vendors. For decades, however, despite the large human resource and financial investment from some super international companies, CAE/CAD integration has not yet been fully realized. As we know, the boundary integral equation method has advantages of naturally seamless connection with CAD packages. Unfortunately, the conventional implementation of the boundary element method is unsuccessful in engineering application. In this paper, a new method to seamlessly integrate CAE/CAD based on boundary integral equations and nonconforming meshes is introduced. The nonconform mesh can effectively promote automatic CAE analysis development, while the dual interpolation boundary face method provides theoretical support for the above technologies. In addition, a spherical subdivision method is proposed to improve the accuracy and stability of singular and near-singular integrals in BIE. Adaptive cross approximation algorithm can reduce the storage of the dense coefficient matrix effectively and approximate the far-field matrix for large-scale computation. Based on the above theories, the "5aCAE simulation software" is developed. In this software, CAE analysis is performed directly on the CAD model using discontinuous mesh without geometric simplifying and repairing, which is impossible for existing commercial software. There is no need to select element types such as beams, shells elements, because any structure is treated as a complete entity. Automation is another feature of this software, which lowers the threshold for users. This paper presents a comprehensive overview of the dual interpolation boundary surface method and introduces the highlights of "5aCAE simulation software", which can provide technical support for boundary element CAE software development.

1. Introduction

Modern industrial systems are heavily dependent on commercial software, wherein finite element method (FEM)-based CAE commercial software, such as Ansys and Abaqus, dominates the market. However, the presently available CAE software lacks substantial automation and is often hindered by mesh generation during pre-processing. In pre-processing, finite element software introduces the abstract elements (e.g., beam elements and shell elements, etc.) that rely on a priori assumptions and require extensive user expertise and experience for successful implementation. Additionally, the adoption of abstract elements will lead to the simplification of original structures, thereby impacting simulation accuracy and rendering the automatic analysis unfeasible. As shown in Fig. 1, due to the different degrees of freedom between plate element nodes and solid element nodes, handling their connections requires introducing new assumptions, resulting in low accuracy in stress at the connection point, where the stress concentration is a key factor determining structural performance (fracture or fatigue). Except that FEM also owns another drawback: I) the accuracy of the result depends on the element shape, II) small features are omitted due to connectivity and aspect ratio, III) accuracy for stresses is of one order lower than displacements, IV) new assumptions are required for connecting different kinds of elements, which induces difficulty in capturing local stress. All these defects make the automatic analysis almost impossible for FEM.

Over the decades, software developers have consistently aimed for

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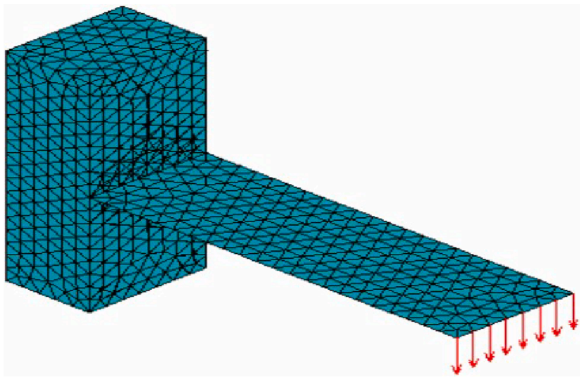


Fig. 1. CAE model of plate and block connection.

CAD/CAE integration. Despite a large amount of investment in this field, the true seamless CAD/CAE integration has remained elusive. Automated mesh generation is a crucial aspect of CAD/CAE integration, and its successful implementation relies on a reliable mesh generation method. However, achieving this goal is challenging in software based on FEM due to the requirement for trial function continuity and the aforementioned drawbacks. The boundary integral equation (BIE) of the boundary element method (BEM) [1,2] allows the trial function to be discontinuous. Therefore, BEM possesses the natural advantage in achieving CAD/CAE integration due to the lack of mesh continuity requirements.

Another crucial aspect of CAD/CAE integration lies in the unification of the CAD model and CAE model, since excessive human interventions are introduced in this process. In conventional BEM or FEM, the CAE model (approximate mesh model) is significantly different from the CAD model (continuous parametric model), not only in geometry and topology, but also in representation data structure. CAD/CAE integration requires an automatic transformation of a CAD model to CAE model, which requires that CAD model without geometric noise. Geometric noise in the CAD model, such as short edges and narrow faces in the second hand of the clock (see Fig. 2), brings out singular and near-singular integral problems [3–9]. In such case, geometry repair must be performed prior to mesh generation. Automated geometry repair is usually more difficult than mesh generation and results in the CAE model no longer being identical to the CAD model in small features.

To avoid the approximation of CAE model, isogeometric analysis is proposed [10,11]. The main idea of the isogeometric analysis (see Fig. 3) is to employ a unified function to approximate the geometry and the physical variables. Therefore, it can be considered as a “huge” isoparametric element that utilizes shape functions derived from various types of splines. The geometry of most industrial products consists of bodies with simple surfaces that can be expressed in closed form functions, which are already available in all CAD packages, such as planar, spherical, conic and cylindrical surfaces, etc. Compulsively converting all these surfaces into spline ones is inconvenient, inefficient and leads to a dramatic increase in data size. In addition, tackling the gaps between mutually trimmed spline surfaces still remains an obstinate challenge for isogeometric analysis.

Combining the BIE with computer graphics, the boundary face method (BFM) [12–15] is presented to avoid the error from the geometric approximation. BFM is a truly isogeometric analysis method, which enables direct CAE analysis to be performed on the CAD model. Fig. 4 illustrates the distinction between FEM and BFM. It can be observed from the figure that BFM preserves the original features at small chamfer, in contrast to FEM that employs isoparametric elements to approximate the geometric model.

To cope with the interpolation problem in small feature size, the dual interpolation method is proposed [16,17]. The dual interpolation combines the traditional element interpolation and meshless approximation [18], while inheriting the advantages and avoiding the disadvantages of

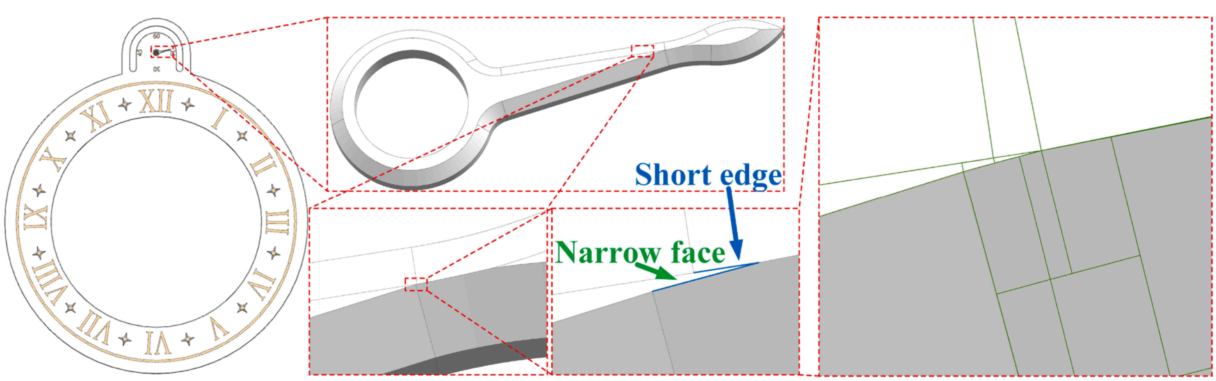


Fig. 2. Geometric defect: (a) short edge and (b) narrow face.

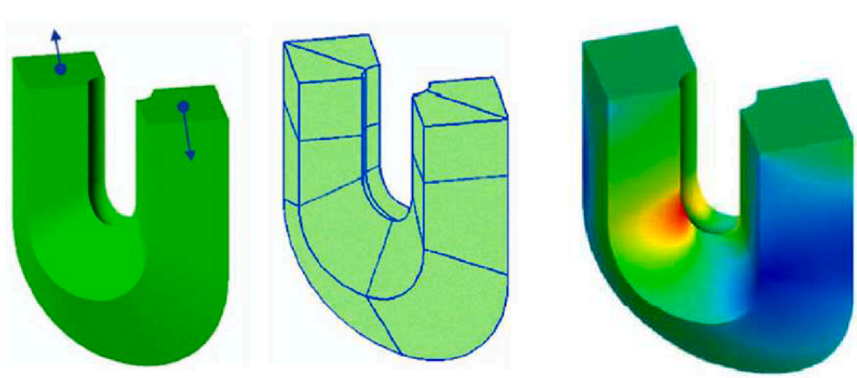


Fig. 3. Isogeometric analysis.

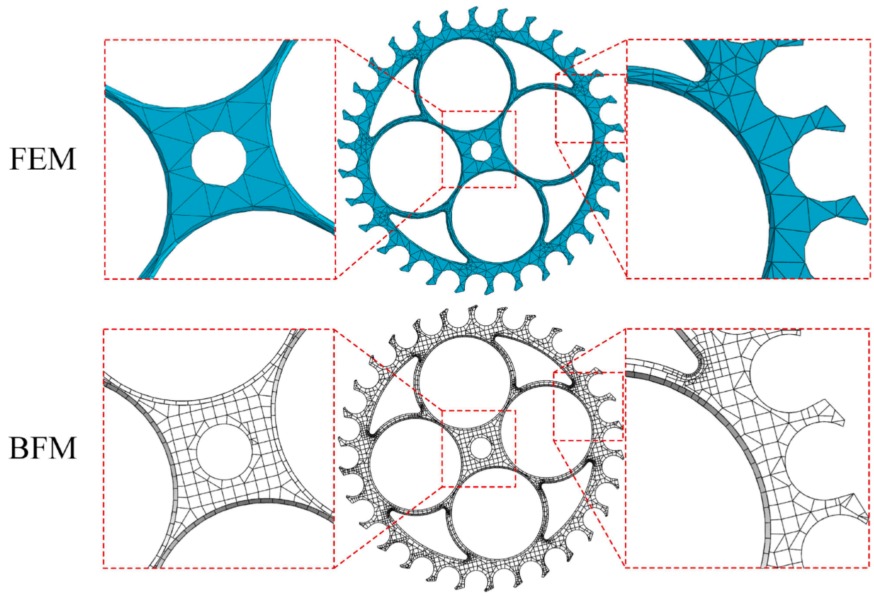


Fig. 4. Difference between FEM and BFM.

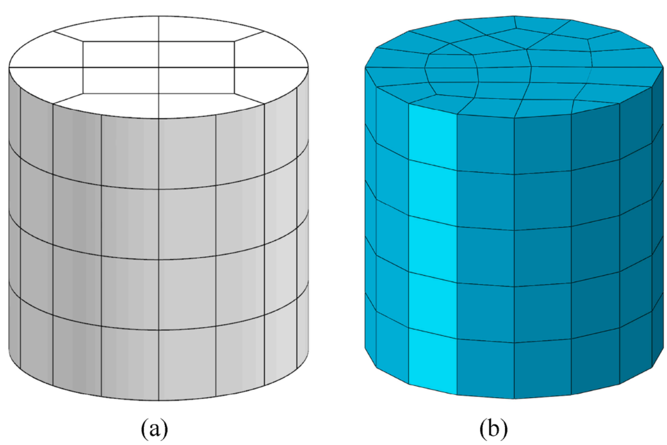


Fig. 5. Discretization of a cylinder: (a) BFM model and (b) BEM model.

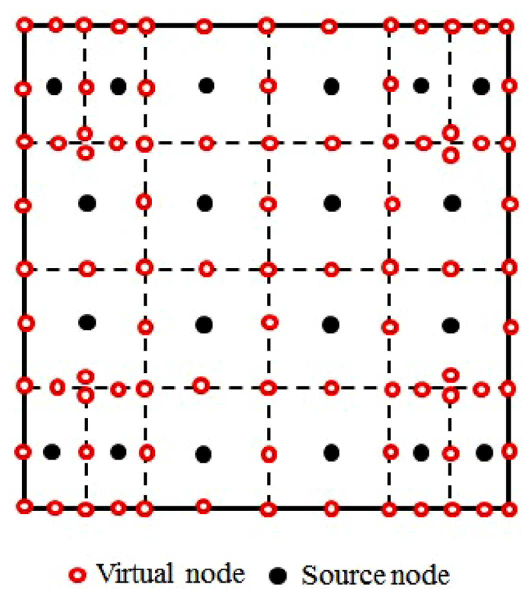


Fig. 6. Dual interpolation element.

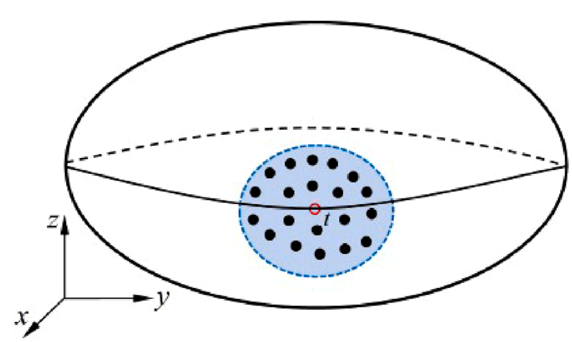


Fig. 7. Diagram of influence domain in meshless interpolation.

both methods. Geometry repair in mesh generation for CAD models is unnecessary in the dual interpolation method. Combining the dual interpolation method and BFM, the dual interpolation boundary face method (DiBFM) [16,19] is introduced, which provides theoretical support for the application of discontinuous mesh.

From all the work mentioned above, our team proposes the concept of "Complete Solid Analysis" [20], and develops automatic software named "5aCAE". This software is able to implement automatic analysis with high accuracy for complex structures and provides a platform for BEM software to catch up with the international advanced business software. The researches on this software include: the dual interpolation boundary face method, automatic mesh division method based on binary tree, parallel computation and fast algorithms based on CPU/GPU.

The rest of this paper is arranged as follows: Section 2 introduces the innovation and breakthrough in algorithm; Section 3 introduces the automatic software 5aCAE; Numerical examples obtained by 5aCAE are shown in Section 4; Sections 5 drafts the conclusions.

2. Innovation of algorithm

Over the past decades, we have achieved breakthrough innovations of the core algorithm in the following aspects.

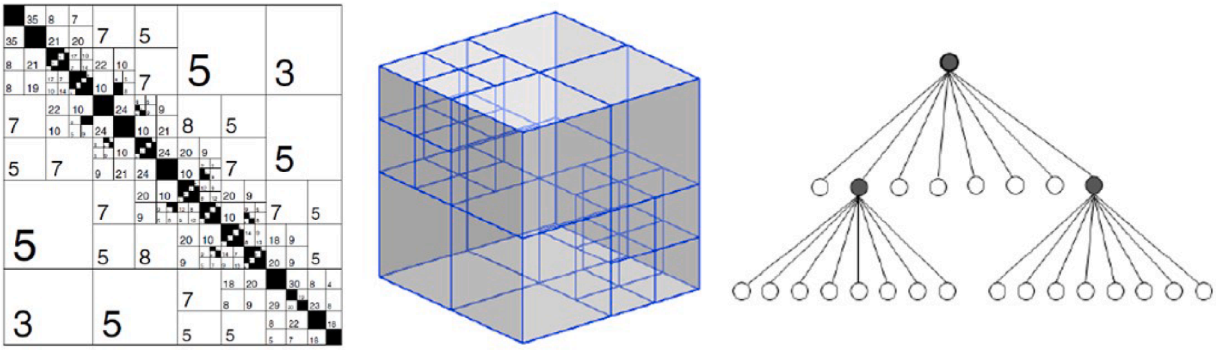


Fig. 8. Hierarchical matrix.

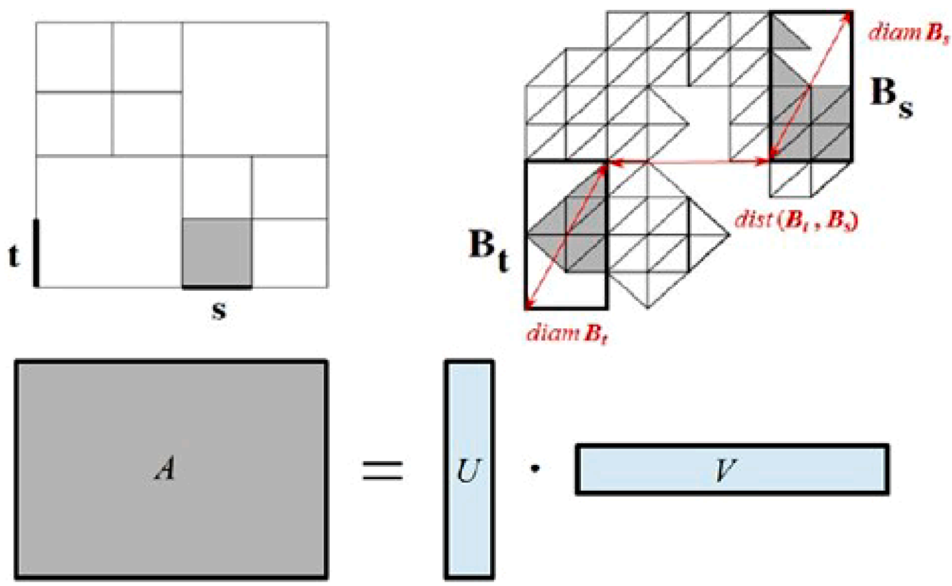


Fig. 9. Adaptive cross approximation.

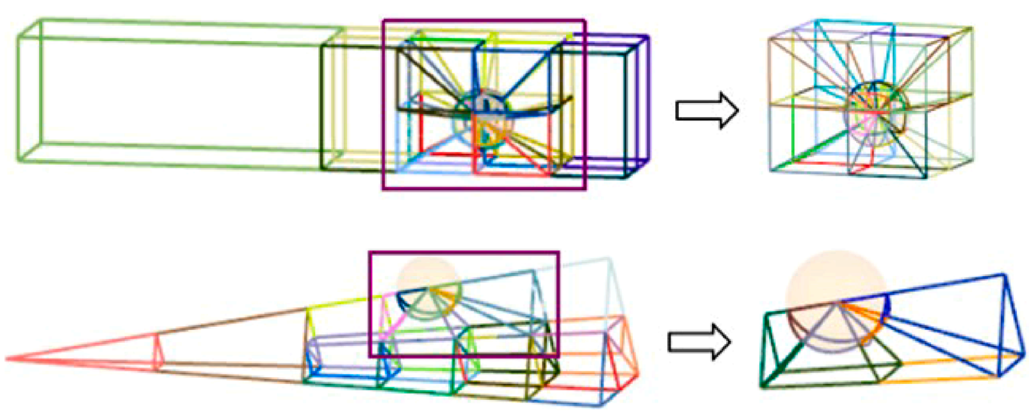


Fig. 10. Spherical element subdivision method.

2.1. The boundary face method

BFM is generated on the basis of BIE and computer graphics. This method takes the advantages of BIE allowing the trial function to be discontinuous, which connect with the data structure of the boundary representation (Brep) of the modeling software seamlessly [4,13,14,20,40–43]. Furthermore, it performs stress analysis directly on the three-dimensional solid model, and CAE and CAD are integrated naturally. In the BFM, the boundary integral and the interpolation of physical quantities are carried out in the parameter space of the surface in the CAD model. All surfaces are divided into a series of sub surfaces in the parameter space. The sub surfaces are called surface patch in graphics and surface elements in the BFM. Such surface elements are similar to isoparametric elements in the BEM, except that the surface elements are located in the parameter space of the surface, while the elements in the BEM are located in the three-dimensional space. From

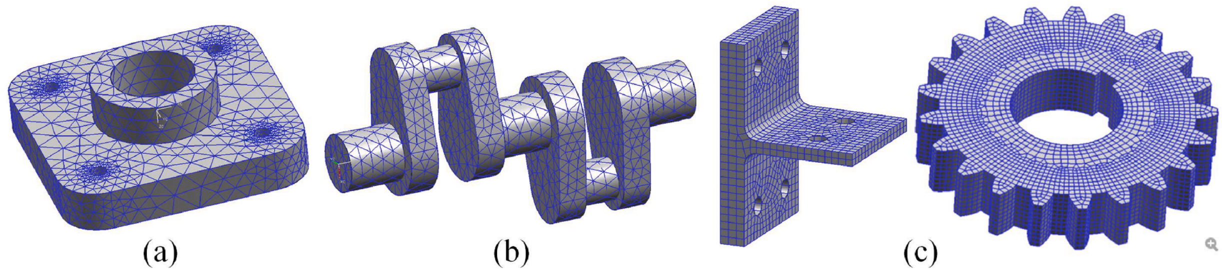


Fig. 11. Continuous meshes: (a) advancing method, (b) Delaunay triangulation method, and (c) sweeping method.

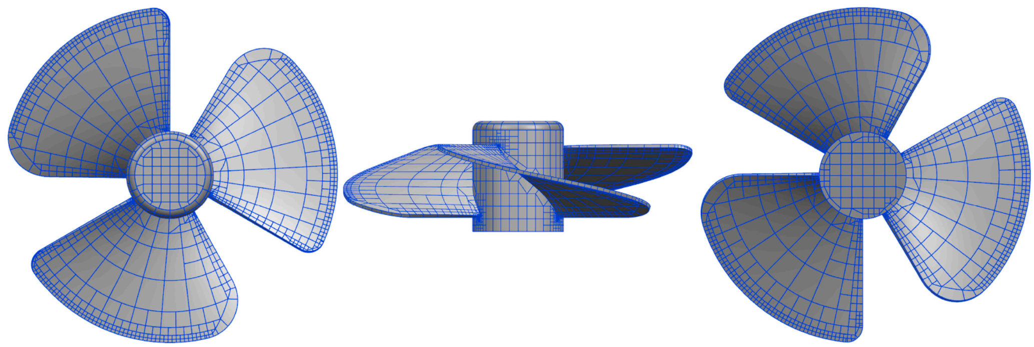


Fig. 12. Discontinuous meshes of air fan.

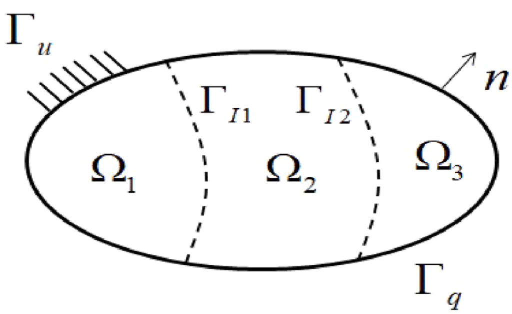


Fig. 13. Multi-domain problem.

Fig. 14. Logo for 5aCAE.

Fig. 5, we can distinguish the difference when a cylinder is discretized by BFM and BEM method with linear quadrilateral elements. The CAE model is consistent with the CAD model in the BFM while the geometric errors are introduced in the BEM.

2.2. The dual interpolation method

The dual interpolation method is divided into the first-layer interpolation (element interpolation) and the second-layer interpolation (meshless interpolation). In the dual interpolation method, the dual interpolation element consists of source and virtual nodes (see Fig. 6). The virtual nodes are located on the edge of the element, and the source nodes are inside in the element. Since the virtual nodes are not regarded as collocation nodes in the BIE, thus the second-layer interpolation based on Hermite-type moving-least-squares method (HMLS) [17] is used to condense the degrees of freedom of virtual nodes. This method unifies the conforming and nonconforming elements in BEM implementation, simultaneously, gives a complete description of the boundary variables in BIE. The dual element needs less source nodes than conventional elements but possesses higher accuracy than the same order element [16,19,44–49]. Not only the dual interpolation method is used to approximate continuous and discontinuous functions, but also it makes the application of the discontinuous meshes possible. Based on its advantages, adaptive meshes are easily to performance, which provide convince for nonlinear problems.

The first-layer interpolation is element interpolation using Lagrange polynomial and the physical quantities are approximated by the source and virtual nodes in an element. This interpolation expression is given below:

$$u(\xi,\eta)=\sum_{i=1}^{n_i}N_i^s(\xi,\eta)u\left(Q_i^s\right)+\sum_{j=1}^{n_j}N_j^v(\xi,\eta)u\left(Q_j^v\right), \tag{1}$$

$$q(\xi,\eta)=\sum_{i=1}^{n_i}N_i^s(\xi,\eta)q\left(Q_i^s\right)+\sum_{j=1}^{n_j}N_j^v(\xi,\eta)q\left(Q_j^v\right), \tag{2}$$

where u and q represent potential and normal flux in potential problems,

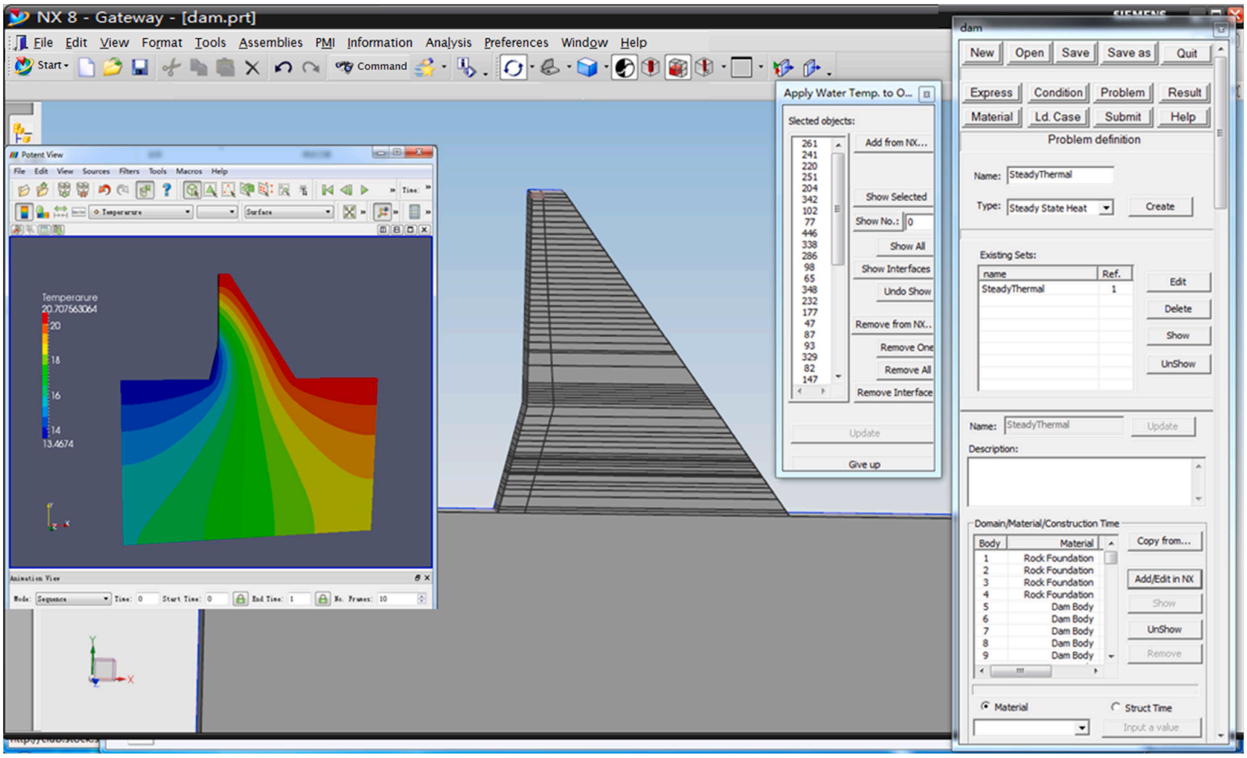


Fig. 15. Software operation panel.

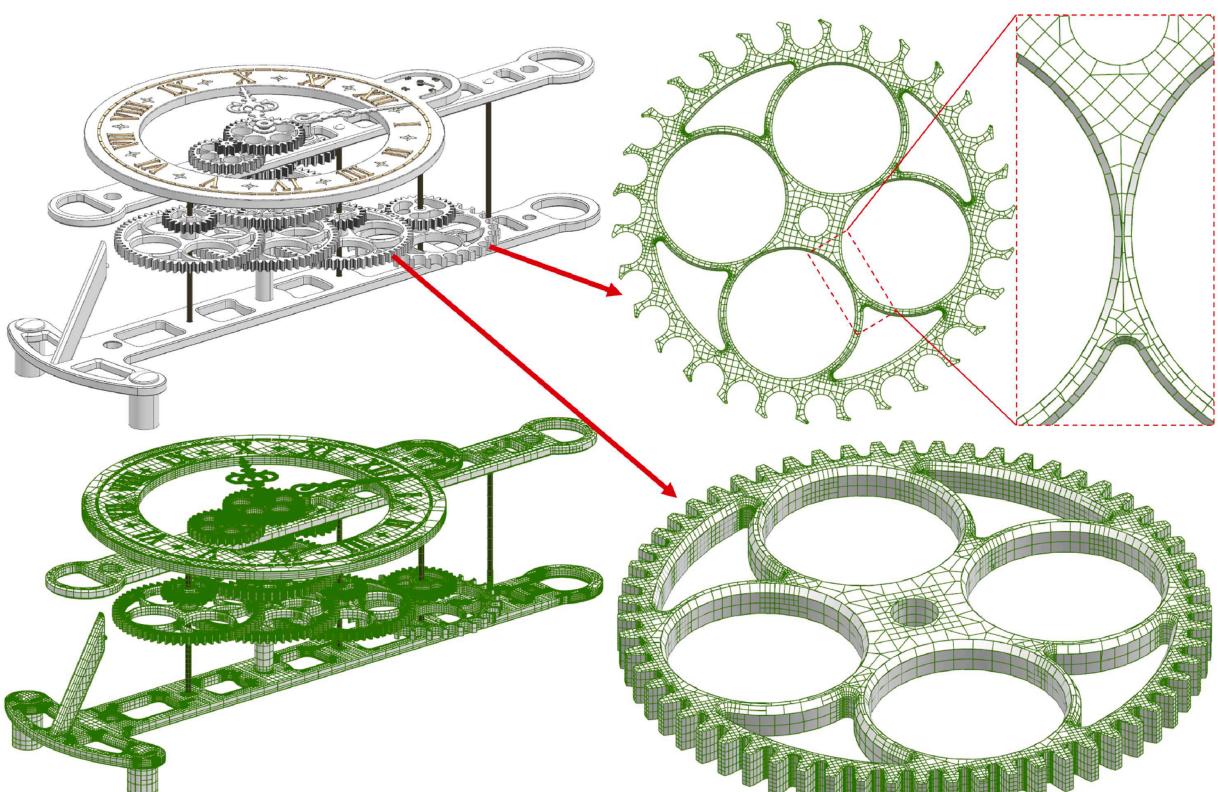


Fig. 16. Discontinuous meshes for multi gear clock.

and displacement and traction in elastic problems. ξ and η are the parameter coordinates, n_i and n_j represent the number of source and virtual nodes, Q_i^s and Q_j^v denote the *i- th* source node and *j-th* virtual node respectively. $N_i^s(\xi,\eta)$ and $N_j^v(\xi,\eta)$ are the shape functions of the source node Q_i^s and the source nodeQ_j^v, respectively.

The second-layer interpolation is meshless interpolation based on the

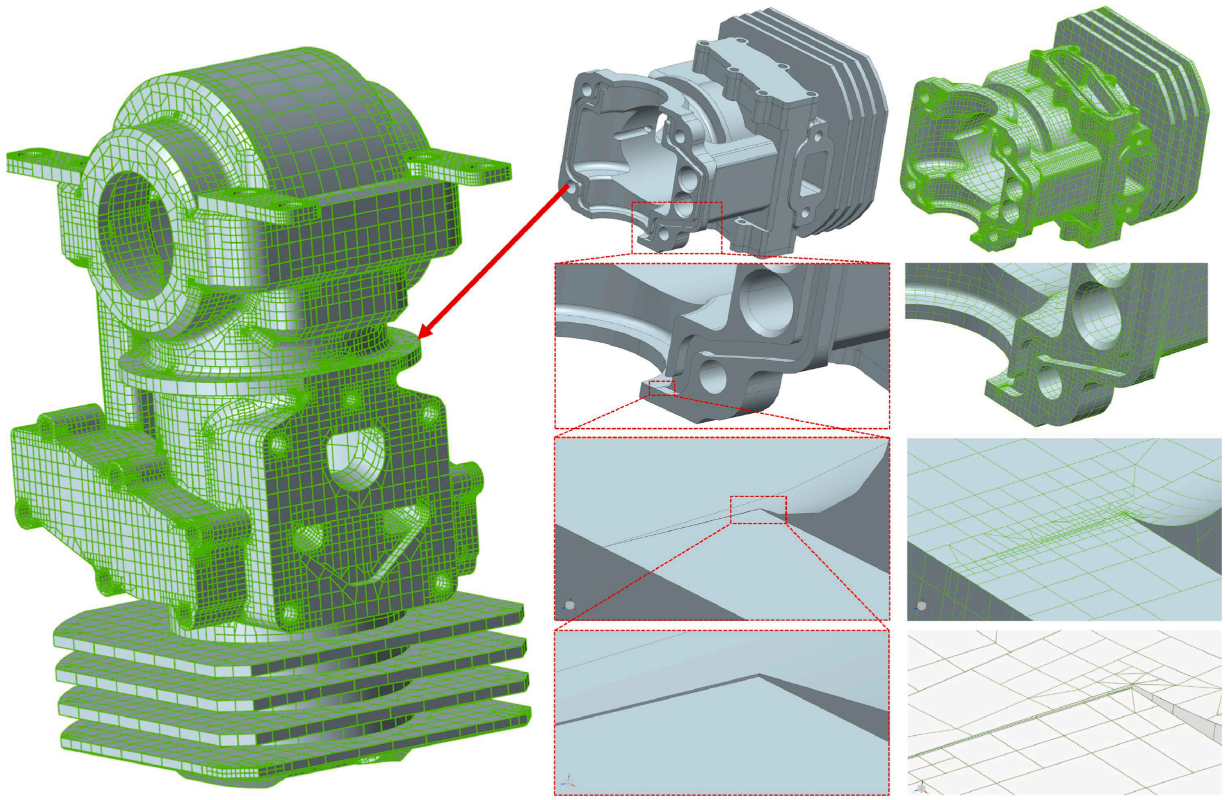


Fig. 17. Discontinuous meshes for Engine shell.

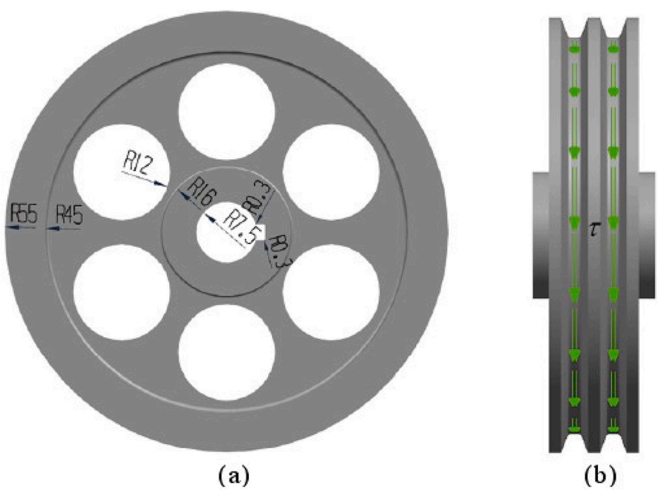


Fig. 18. (a) Geometric model for pulley and (b) its boundary conditions.

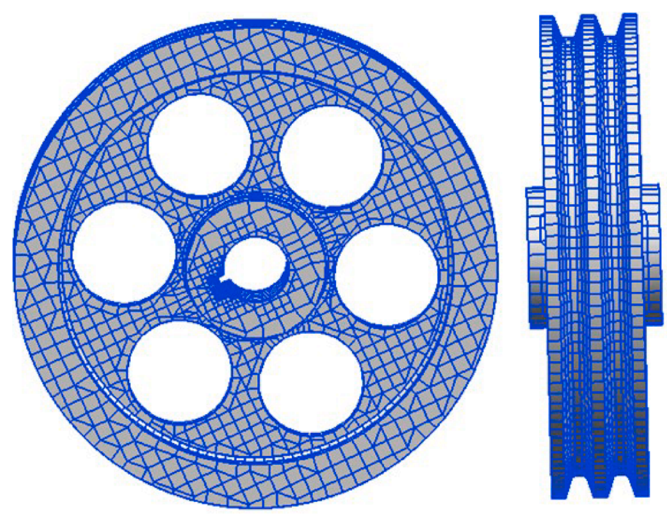


Fig. 19. Discontinuous meshes for pulley.

Hermite-type moving-least-squares method. In this interpolation, the relationship between an arbitrary virtual node t and the source nodes in the influence domain (see Fig. 7) is established.

Different from the traditional MLS method, the HMLS method directly uses Cartesian coordinates to establish the shape function, and gets rid of the limitation that the influence domain can only be on curves or surfaces. This interpolation expression is given below:

$$u(Q_t^v) = \sum_{I=1}^{M} \phi_I^{uu}(x^v, y^v, z^v)\widehat{\phi}(Q_I^s) + \sum_{I=1}^{M} \phi_I^{uq}(x^v, y^v, z^v, n^v)\widehat{q}(Q_I^s), \tag{3}$$

$$q(Q_t^v) = \sum_{I=1}^{M} \phi_I^{qu}(x^v, y^v, z^v)\widehat{\phi}(Q_I^s) + \sum_{I=1}^{M} \phi_I^{qq}(x^v, y^v, z^v, n^v)\widehat{q}(Q_I^s), \tag{4}$$

where Q_t^v represents the current interpolated virtual node t, M is the number of source nodes located in the influence domain, x^v, y^v, z^v and n^v are the Cartesian coordinates and the outward normal, respectively. $\phi_I^{uu}(x^v, y^v, z^v)$, $\phi_I^{uq}(x^v, y^v, z^v, n^v)$, $\phi_I^{qu}(x^v, y^v, z^v)$ and $\phi_I^{qq}(x^v, y^v, z^v, n^v)$ are the shape functions of HMLS interpolation [48,49].

2.3. Fast algorithm

Since the coefficient matrix of BIE is an asymmetric full matrix, it is difficult to apply the boundary element method to solve large-scale problems. Fast algorithms [6,14,50,51,53,59] such as fast multipole method (FMM) and adaptive cross approximation (ACA) are proposed to

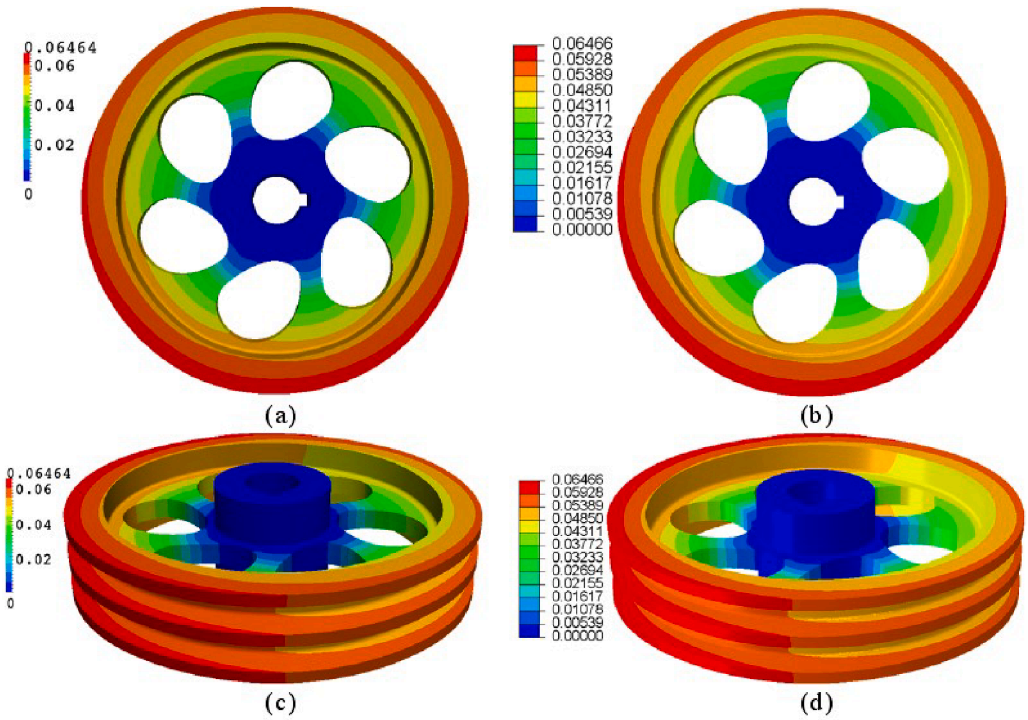


Fig. 20. Displacement for pulley: (a) (c) 5aCAE with 19,784 source nodes, (b) (d) ABAQUS with 2,644,050 nodes.

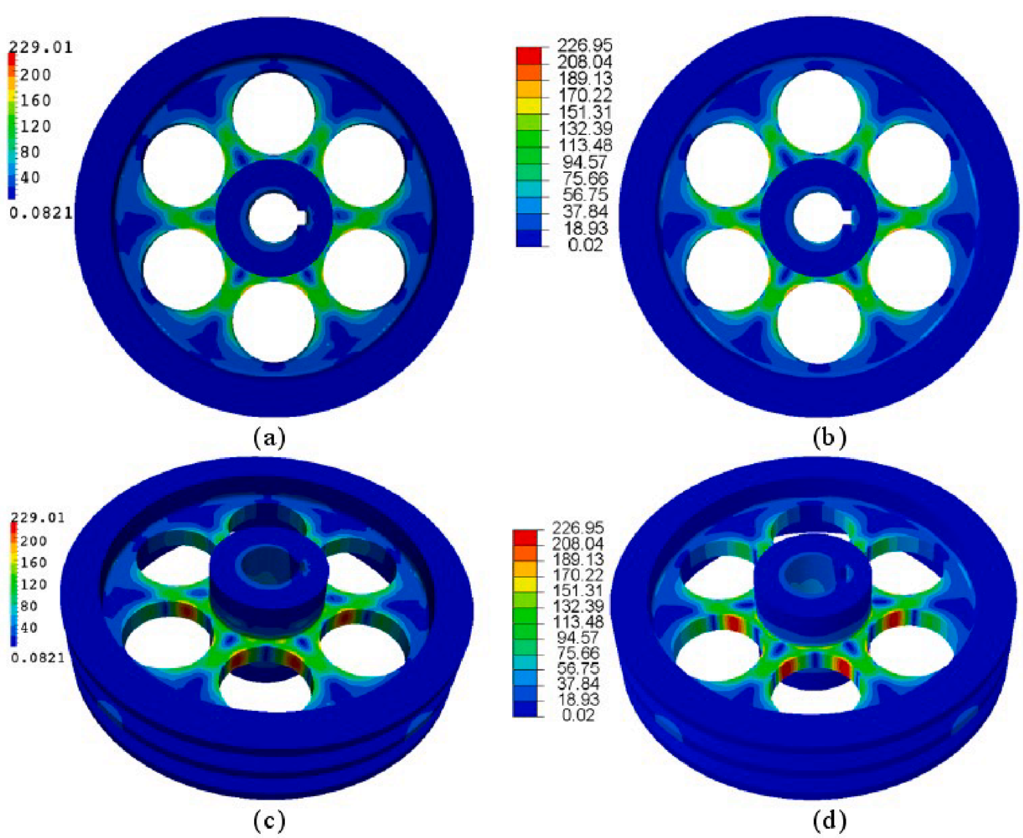


Fig. 21. Von-Mises stress for pulley: (a) (c) 5aCAE with 19,784 source nodes (b) (d)ABAQUS with 2,644,050 nodes.

reduce the computational complexity of the BIE to linear or almost linear magnitude. Unlike FMM, ACA does not require series expansion of the kernel function and is a purely algebraic algorithm for different physical problems. All algebraic operations are based on the hierarchical matrices [60] (see Fig. 8). Through the employment of the low rank approximation technique (see Fig. 9), the far field matrix blocks with

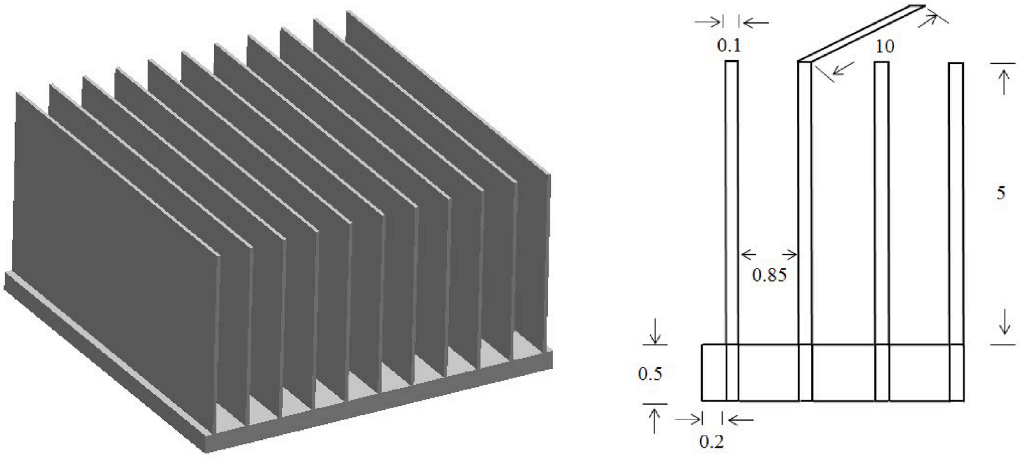


Fig. 22. Geometric model for sink.

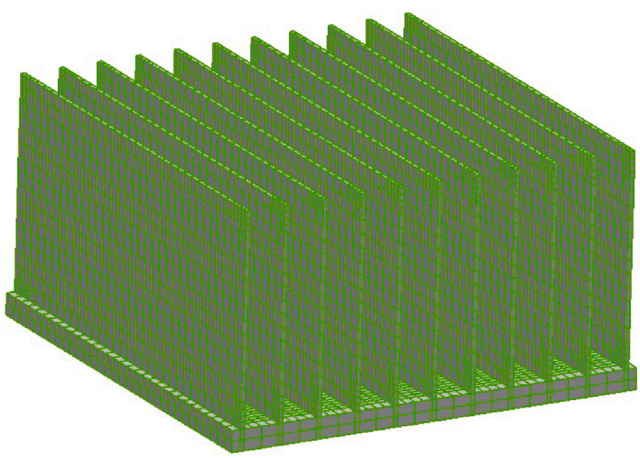


Fig. 23. Discontinuous meshes for sink.

low rank are stored in the form of cross product of two low rank matrices, thus the computational complexity and memory can be greatly reduced.

2.4. The spherical element subdivision method

The spherical element subdivision method (see Fig. 10) uses the binary tree structure to generate the patch for the numerical integration [25,26,52,54,55]. This method can obtain accurate calculation of singular, hyper-singular or near-singular integrals [64,65] for continuous or discontinuous kernel, any element shape, and any location of source node. Owing to this method, it is no longer the difficulty to compute the singular integral in the boundary integral equation and can guarantee the convergence of successful element subdivision for any situations.

2.5. Automatic meshing of complex structures

In our software, several traditional mesh generation methods (see

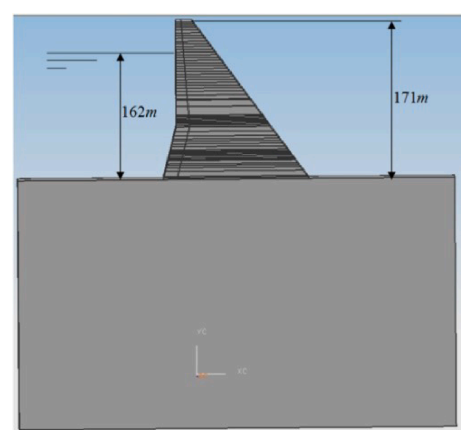


Fig. 25. Geometric model for dam.

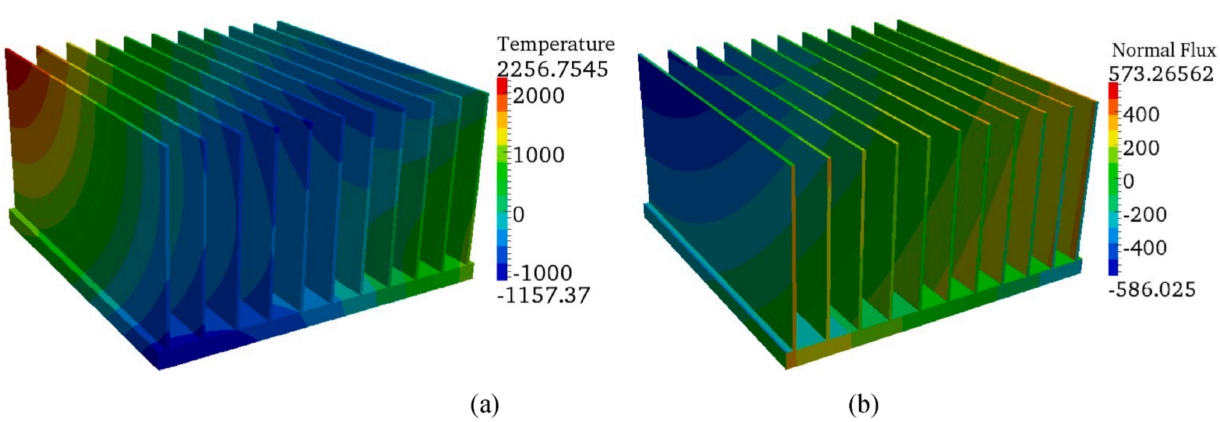


Fig. 24. Contours of (a) temperature and (b) normal flux of the sink.

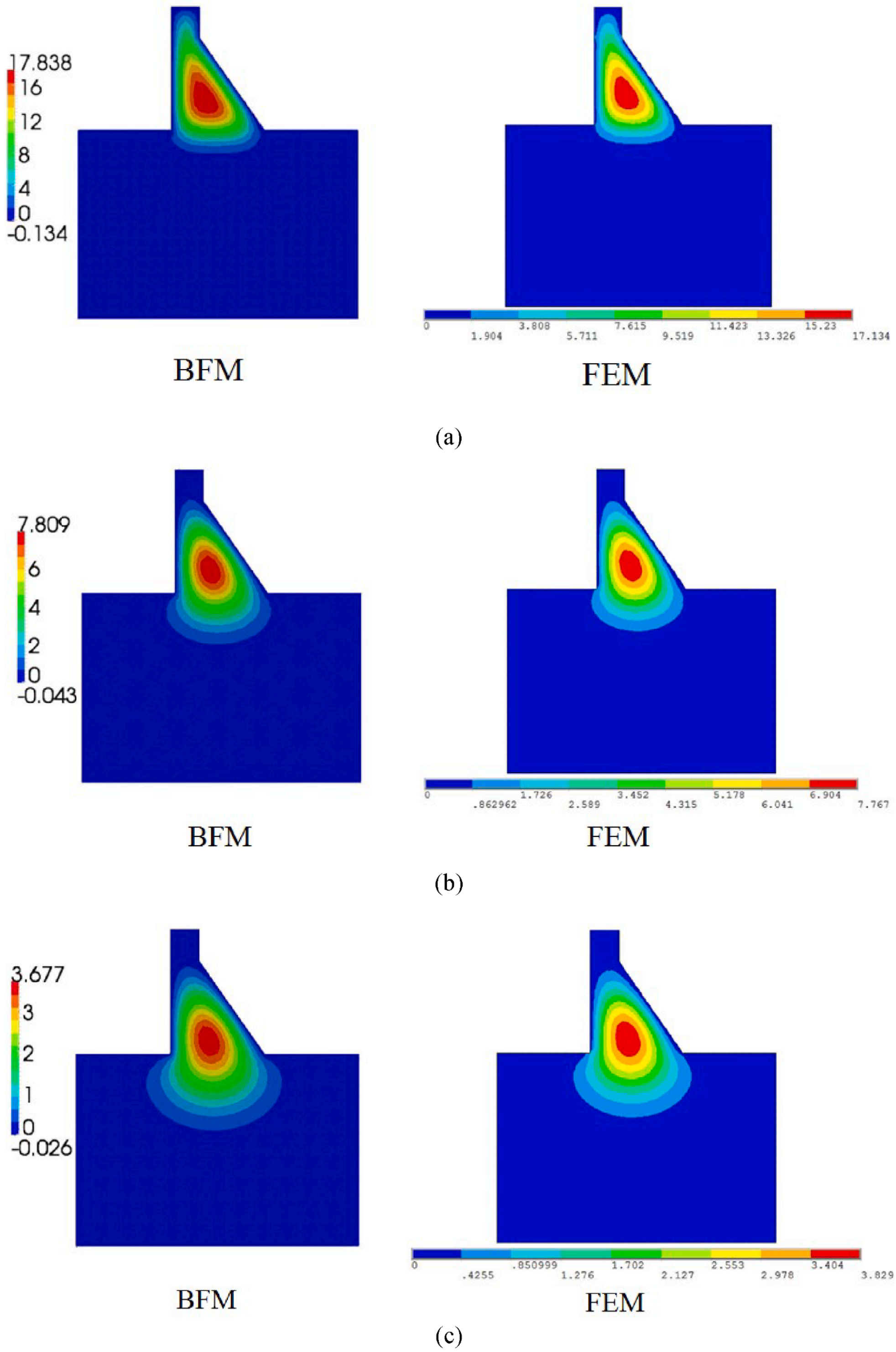


Fig. 26. Heat conduction process: (a) at year 1, (b) at year 3 and (c) at year 5.

Fig. 11) have been implemented, such as Advancing front method, Delaunay triangulation method, Mapping method, Sweeping method, Paving method, Template method, and hybrid methods. Simultaneously, a discontinuous mesh method (see Fig. 12) is presented based on the binary tree structure [56]. This method scarcely depends on the shape of the geometric model and the quality of CAD modeling [29,32,33,57,58]. For arbitrary complex structure, it can guarantee an automatic mesh division. The discontinuous mesh method promotes the progress of CAD/CAE integration.

2.6. *Domain decomposition method*

Domain decomposition method (DDM) is one of the main methods for solving multi domain problems (see Fig. 13) due to its reduction in computation time and memory [61–63]. As an iterative method, there is a relaxation parameter in DDM to affect the convergence. Using dynamic relaxation parameters obtained by error analysis can avoid prior determination of the relaxation parameter. Besides, by implementing DDMs into the frame of DiBFM, one difficulty of DDM, the problem of

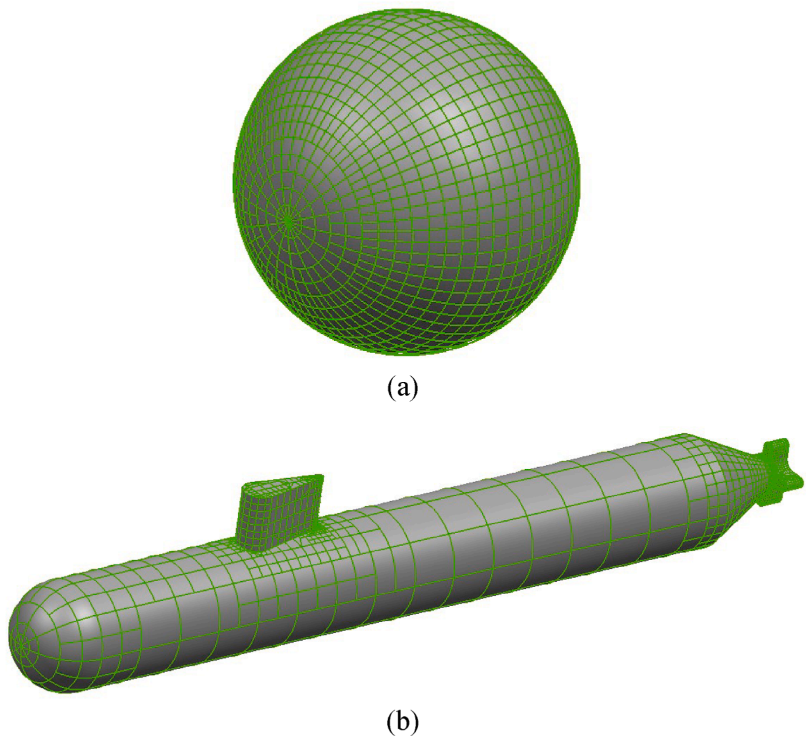


Fig. 27. Discontinuous meshes of (a) sphere and (b) submarine.

interior cross-points, can be avoid.

3. About 5aCAE

Why is it called "5aCAE"? Because it possesses five characteristics (see Fig. 14): automatic, accurate, arbitrary, accelerate, and adaptive.

Automatic: the function of automatic mesh division.

Accurate: high precision and accurate stress analysis.

Arbitrary: avoiding geometric repairing and simplification for arbitrarily complicated structures.

Accelerate: fast solving based on fast algorithm.

Adaptive: the function of adaptive analysis.

Interested readers can visit our website (http://www.5aCAE.com) for details.

3.1. The scale of 5aCAE

In this software, we can integrate our CAE package into the CAD environment completely by including the data structure of the target modeling software. The framework of the CAE analysis is self-developed, and all codes are developed by C++. So far, there are 135 projects, nearly 3000 source files, 5000 classes, and a total number of 1.2 million lines of codes. It includes the basic components of the complete CAE analysis from geometric model to post-processing. This software provides a seamless computational mechanics platform for CAD/CAE integration, and avoids the artificial assumption as much as possible.

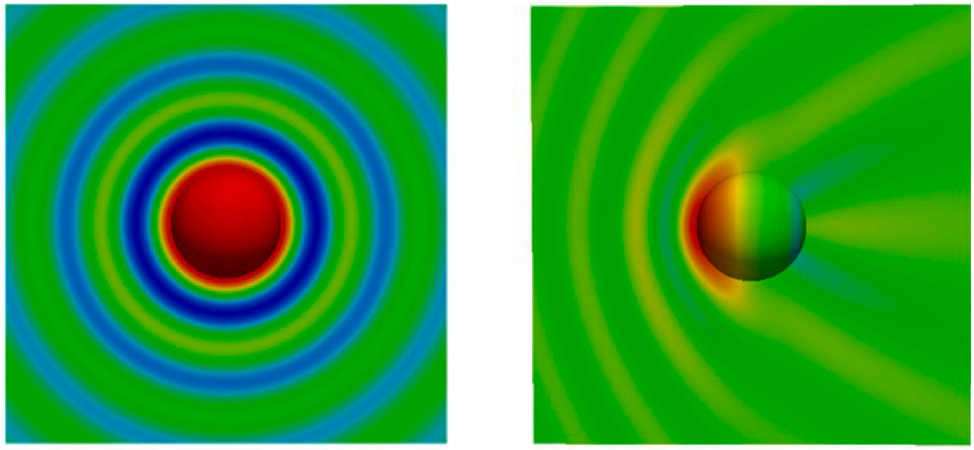
3.2. The functions and advantages of 5aCAE

At present, the 5aCAE can be used to solve the steady-state, transient heat conduction, elastic stress, crack propagation, and steady-state acoustic field for arbitrarily complex structures. At present, 5aCAE software has been successfully applied to engineering problems such as heat conduction [21–26], elastic [20,27], acoustics [28–30], multi-domain [31-33], elastic dynamics [34], contact problem [35–37] and crack growth [38,39]. We plan to implement the geometric nonlinear problems, electromagnetic field, electromagnetic wave problems, multi-physics coupling problems within ten years, and the parallel computing based on CPU/GPU. In the future, it can be combined with big data and cloud computing to form a set of engineering analysis software which can come up with the existing commercial CAE software.

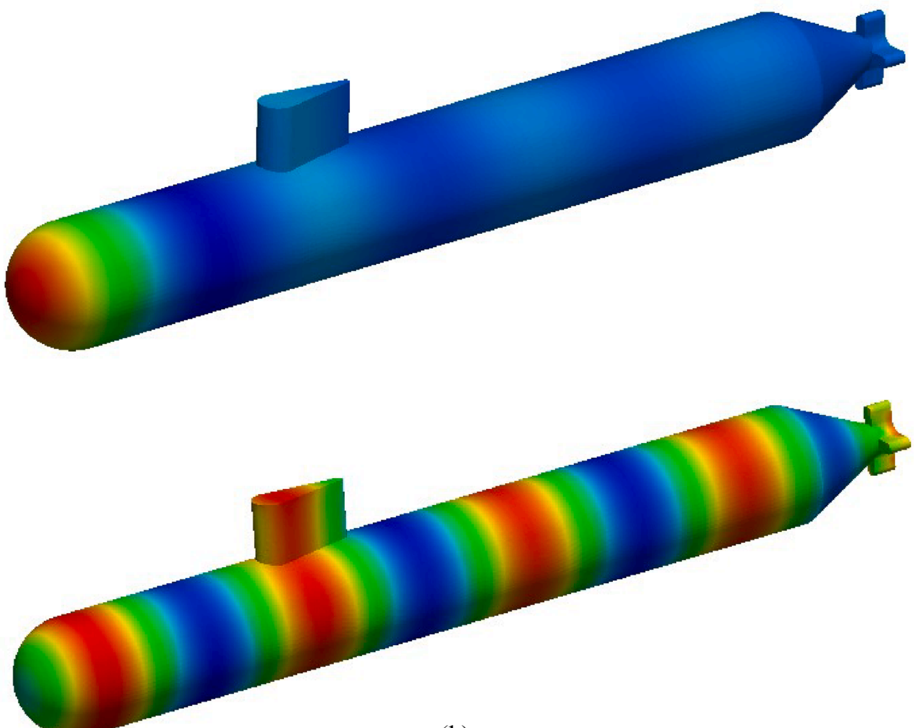
For these functions of 5aCAE, we give an elaborate description as follows:

1) CAE analysis is performed on CAD model directly to avoid the geometric simplification in FEM, and any structures can also be treated as a 3D entity according to its practical shape and size, even for structures with small features (i.e. small chamfer, welds, undercut, and small holes).
2) The mesh can be generated directly without geometric repairing and inputting fewer parameters, even though the geometric model contains "noise" (i.e. overlap, narrow slit and short edge).
3) Avoiding using abstract structure (such as the beam or bar in 1D, and the plate or shell in 2D) to simplify geometric model in CAE analysis, and the analysis is only implemented on three-dimensional entities.
4) Our software can simulate the stress concentration problems accurately in structures with small features (such as small chamfer and thin wall etc.)
5) Conveniently and naturally to simulate the infinite domains problems (such as noise, earthquakes, and electromagnetic waves, etc.)
6) Conveniently to solve the singularity problems (such as getting the strength intensity factor and simulating the crack propagation, etc.)

Besides, 5aCAE has a simple operation interface and friendly for users. The overall operation interface is shown in Fig. 15. The functions of all the buttons are briefer and more explicit than FEM software ABAQUS and ANSYS. The complete analysis steps are same as other business software, including defining material parameter, assign boundary condition, defining problem types, mesh division, element selection, submitting defined problem to analysis, and viewing analysis results. Simultaneously, we integrate some checking function in "Help" column to help user choosing the target face, elements or points for



(a)



(b)

Fig. 28. Sound pressure distributions of (a) sphere and (b) submarine.

viewing purpose. Based on the viewing software *ParaView*, we developed post-processing program which not only can implement the basic function such as plotting all kinds of physical field fringe, but also can show us the distribution of stress intensity. In summary, except the absence of some functions in physical (but these functions are under developing), the 5aCAE has possessed complete analysis capability and can meet some basic analysis requirement. A more detailed description of our software will be given below.

The forthcoming Potent1.0 not only has higher calculation accuracy and efficiency than mainstream international commercial software (such as ABAQUS, NASTRAN and ANSYS, etc.), but also has the following brand-new features which are different from all existing CAE software:

Only a few of operation in the CAD interactive environment can a simple CAE analysis for target problem be completed. The 5aCAE software has low barrier for its users. Even though you don't own the specialized knowledge of the computational mechanics, you can obtain a satisfying result by our software. Only you are familiar with the material mechanics and know how to apply the constrain conditions and load conditions correctly.

Applying constraints and load conditions is performed in the CAD environment. Different from other software based on FEM, the boundary condition is applied directly and intuitively on the geometry, not on the mesh nodes. In our software, the mesh is generated automatically using binary-tree method, and it is invisible to the user. Thus, the user just needs to input initial parameter and need not to care about the process of mesh division.

For complex structures such as rigid frames, we can obtain the accurate stress values at any point on the local weld. Except that, the 5aCAE can study the influence on the structural strength when adopting different welding manners. Simultaneously, since the CAE analysis is always carried out in the CAD interactive environment, you can modify the structure according to the simulation results immediately, and implement the optimal design through repeating above process.

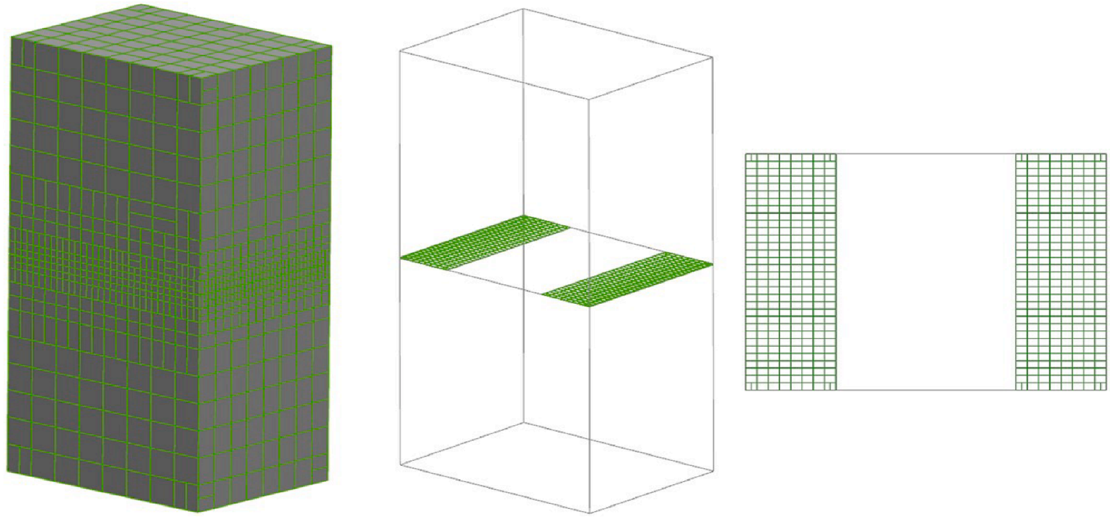


Fig.29. Discontinuous meshes for bilateral crack model.

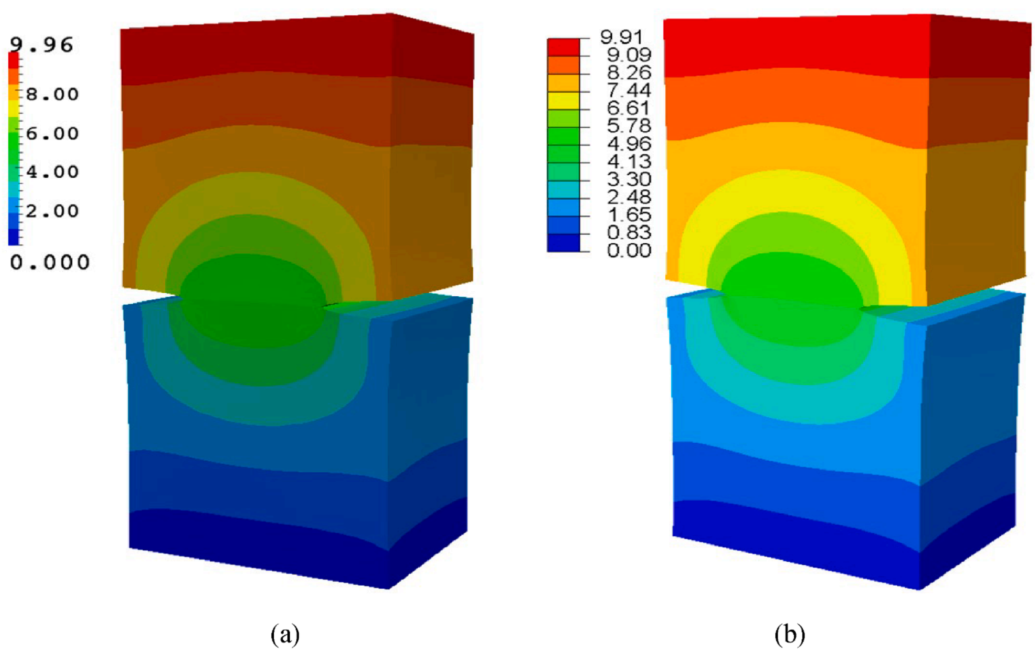


Fig. 30. Displacement for bilateral crack model: (a) 5aCAE with 2704 source nodes (b) ABAQUS with 1,125,833 nodes.

However, the 5aCAE software has its shortcomings. For instance, if structures with 1D or 2D features are all modeled with the 3D BFM, it will cost more computing resources, and using continuous meshes often achieves higher accuracy than using discontinuous meshes when only the mesh continuity is considered.

4. Numerical examples

In this section, we will present some examples to demonstrate the functions of our software.

4.1. Discontinuous meshes

In our software, we adopt the discontinuous meshes to analyze engineering problem. The discontinuous mesh is adaptable and easily to be implemented for arbitrary complex structure. Even for structures with defects, it can guarantee an automatic mesh division. This mesh method makes it possible for automatic CAE analysis. Figs. 16 and 17 show some examples in engineering problem, where the discontinuous meshes are automatically generated without any geometric simplification and cleaning. Simultaneously, the DiBFM provides basis algorithm for the application of the discontinuous meshes.

4.2. Elastostatics problem

This example is the stress concentration problem of the pulley under shear force, and its geometric model and loading mode are shown in Fig. 18. Automatic mesh generation and local mesh refinement are shown in Fig. 19. Contour plots in Figs. 20,21 present the comparison of displacement and Von-Mises stress calculated by 5aCAE and ABAQUS, from which we can note that our software can obtain a comparable simulation only using 19,784 nodes to ABAQUS with 2,644,050 nodes for the elastostatics problem of pulley.

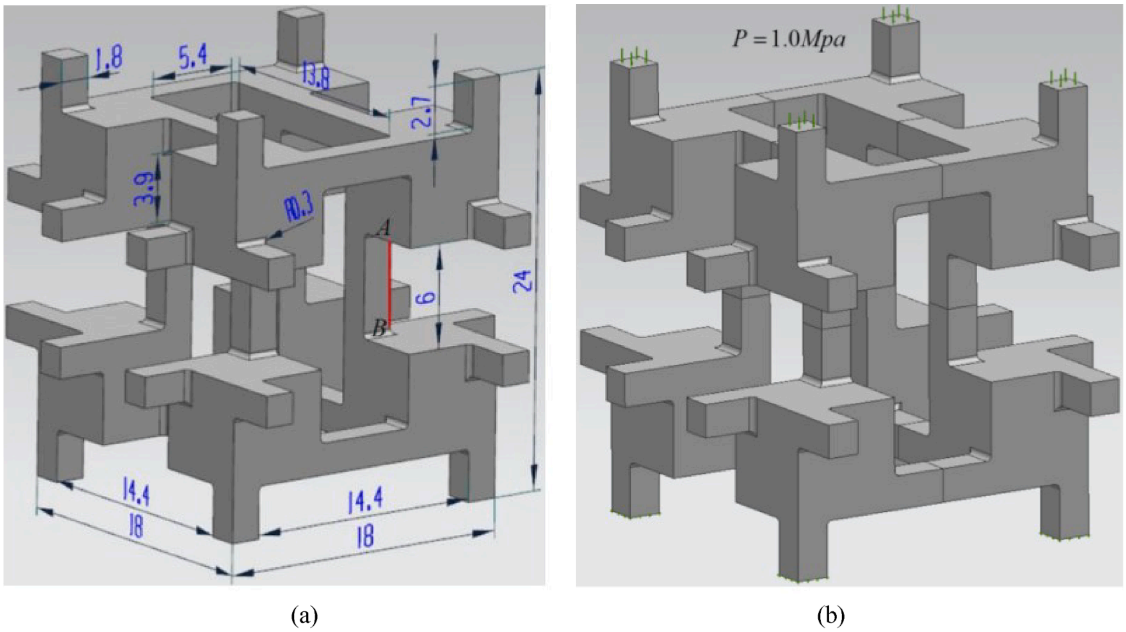


Fig. 31. (a) The geometry of the multi-domain model and (b) its boundary conditions.

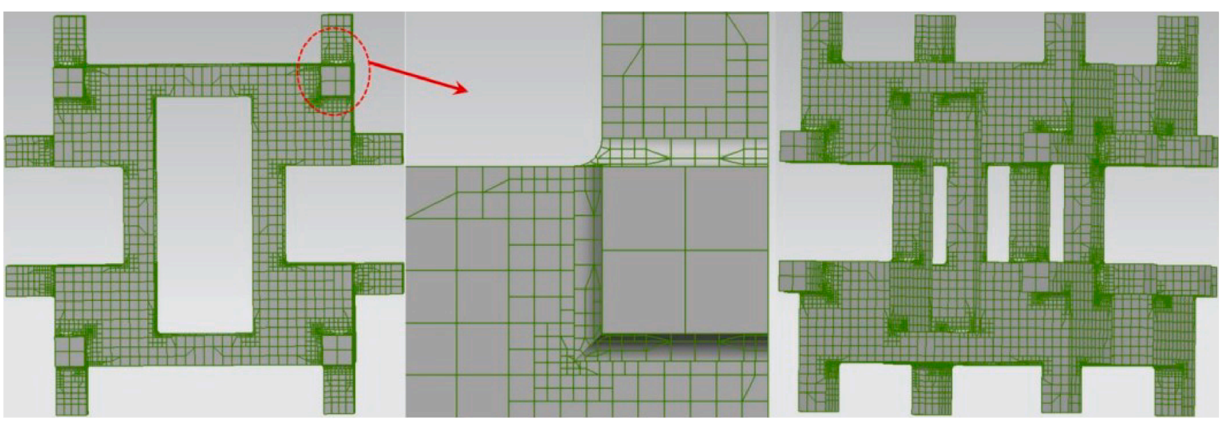


Fig. 32. Discontinuous meshes for the multi-domain model.

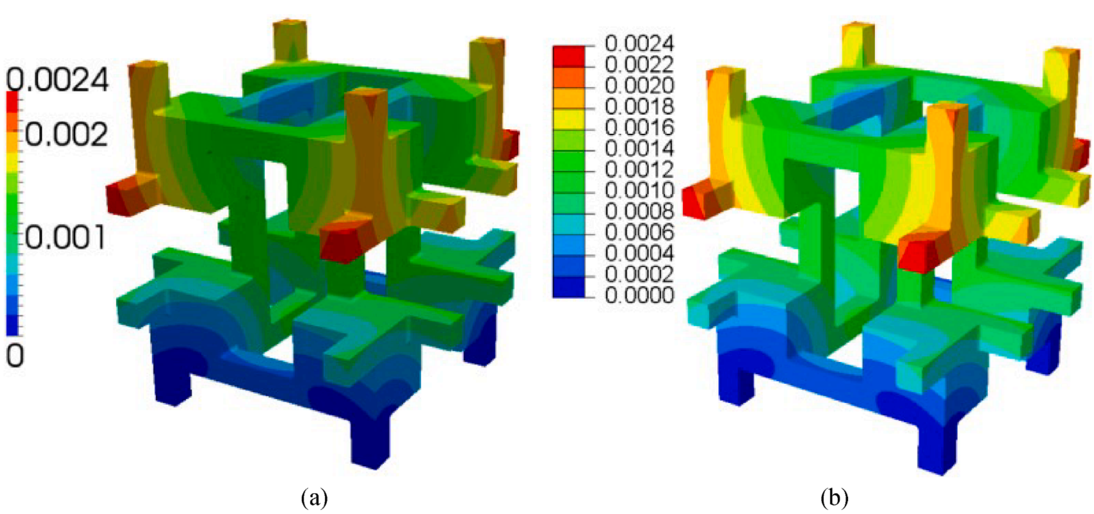


Fig. 33. Displacement for the multi-domain model: (a) 5aCAE with 46,312 source nodes, (b) ABAQUS with 7,259,424 nodes.

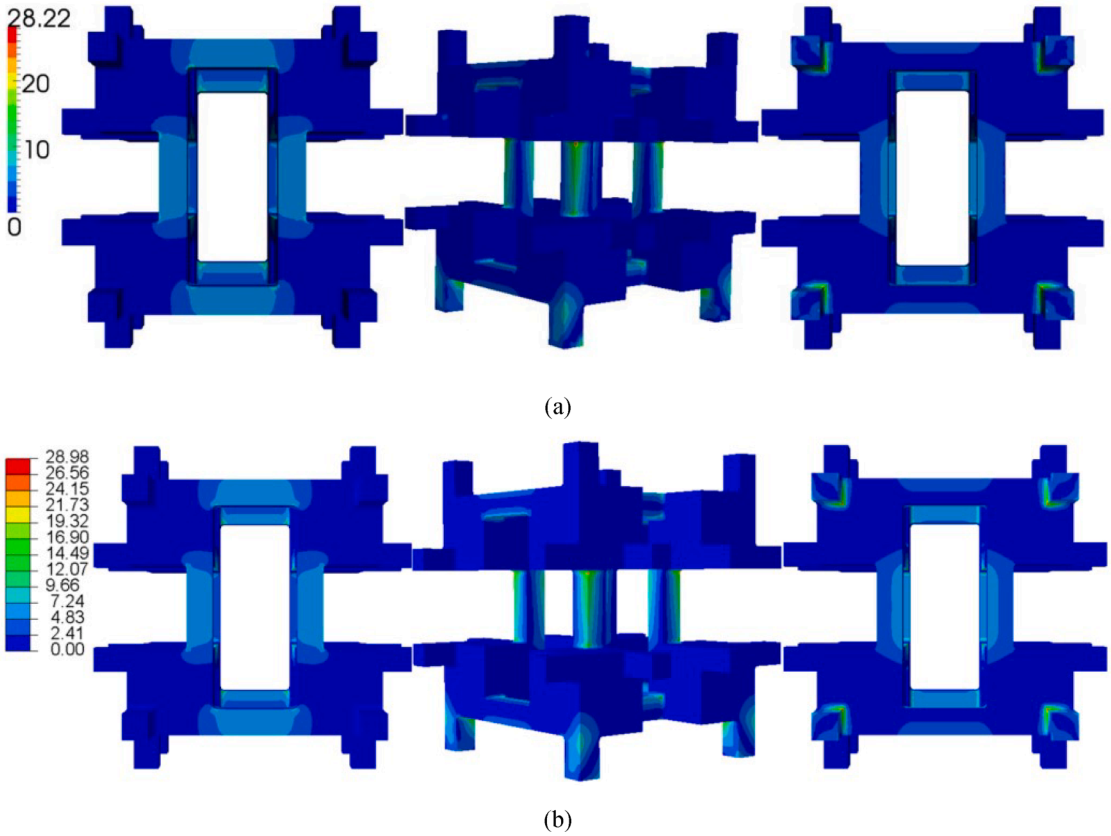


Fig. 34. Displacement for the multi-domain model: (a) 5aCAE with 46,312 source nodes, (b) ABAQUS with 7,259,424 nodes.

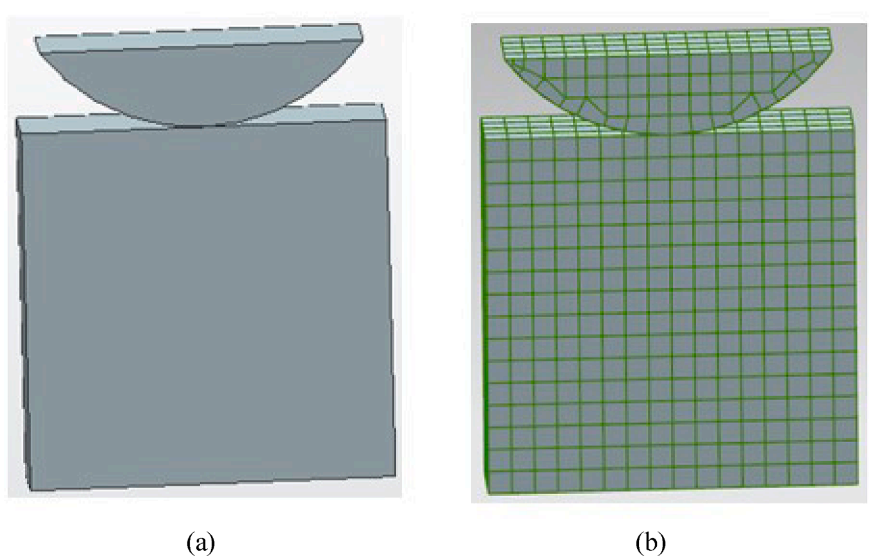


Fig. 35. (a) Contact model and (b) its initial discontinuous meshes.

4.3. *Heat conduction problem*

4.3.1. *Steady state heat conduction problem*

From the Fig. 22 it can be seen that the thinnest wall of the sink is 0.1 mm, which is only 1 % of the maximum size of the sink. Fig. 23 shows the binary tree meshes of the sink. The analytical boundary conditions of potential and flux are used for reference solutions and their forms are given below:

$$u = x^3 + y^3 + z^3 - 3x^2y - 3y^2z - 3z^2x, \tag{5}$$

$$q = -k\frac{\partial u}{\partial n} = -k\left(q_x n_x + q_y n_y + q_z n_z\right), \tag{6}$$

where

$$q_x = 3x^2 - 6xy - 3z^2, q_y = 3y^2 - 6yz - 3x^2, q_z = 3z^2 - 6xz - 3y^2, \tag{7}$$

and k denote the heat conductivity.

Fig. 24 shows the distribution of temperature and flux of the sink. This example demonstrates the capability of our software in solving

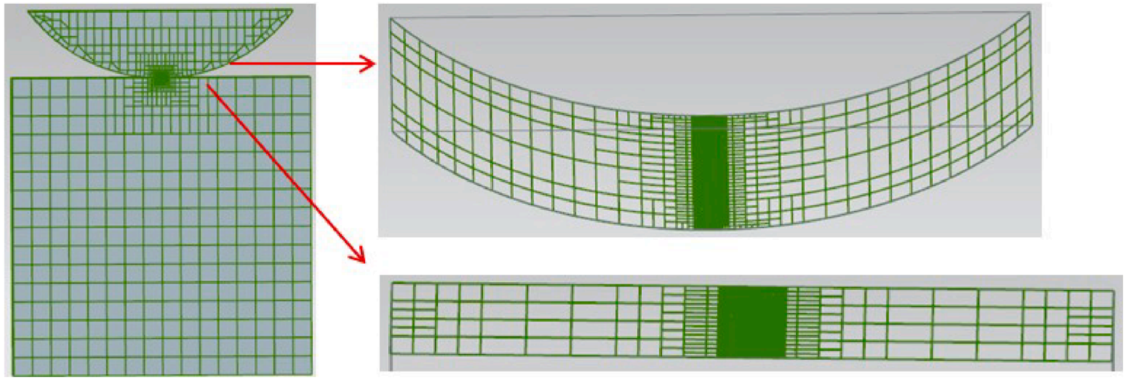


Fig. 36. Automatic mesh refinement in the contact area.

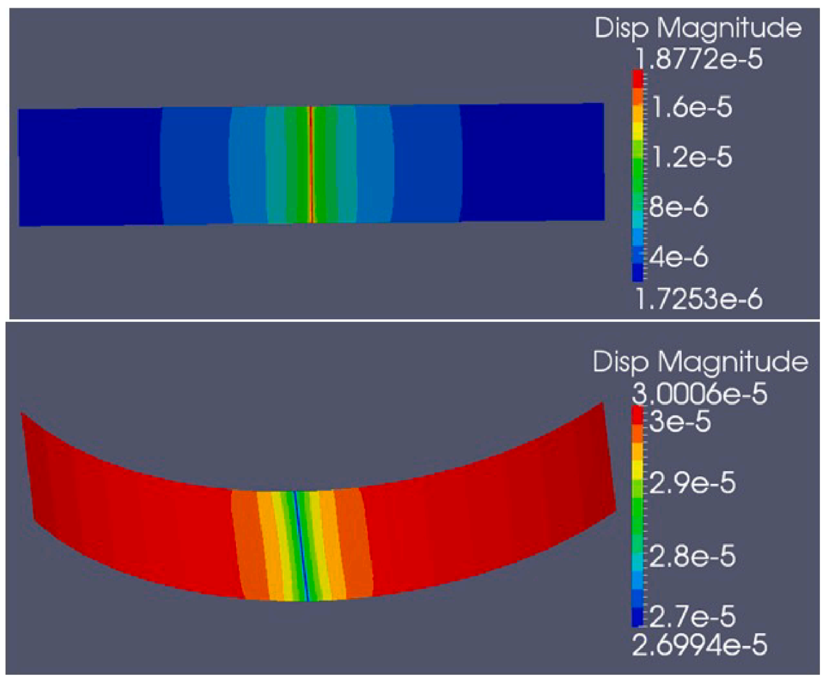


Fig. 37. Displacement distribution of the contact surface.

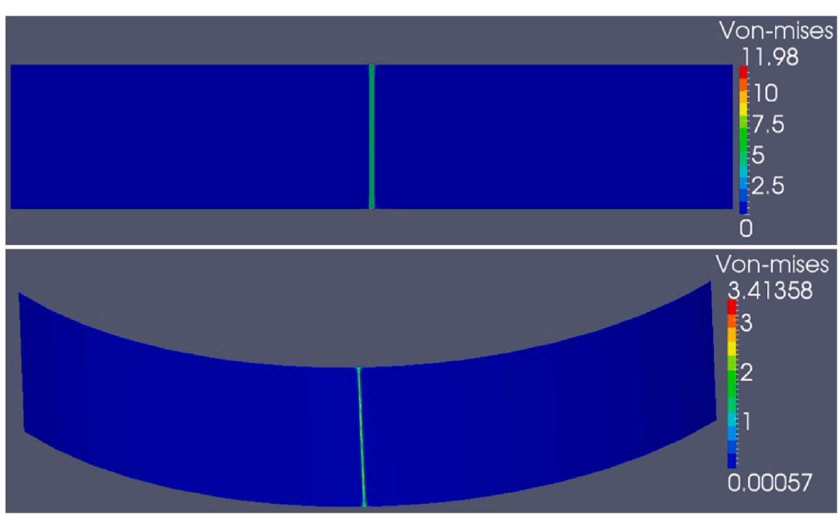


Fig. 38. Von-Mises stress of the contact surface.

steady state heat conduction problem with thin structures.

4.3.2. Transient heat conduction problem

This example based on a real dam simulation as shown in Fig. 25. Distribution of temperature in the dam and the bedrock is studied during 5 years. 5 years is divided into a total of 1260 time steps. Fig. 26 shows the distribution of the transient thermal at year 1, year 3 and year 5. This numerical example successfully simulates a natural cooling process of a dam, and shows that 5aCAE has certain application value in transient thermal analysis of engineering structure.

4.4. Acoustic problem

Fig. 27 shows the discontinuous meshes of the sphere and submarine. The sound pressure distributions of submarine and sphere are shown in Fig. 28. By combining fast algorithms, our software will be able to achieve fast solutions for large-scale acoustic problems.

4.5. Crack problem

Discontinuous meshes for bilateral crack model as shown in Fig. 29. Fig. 30 shows counter plots of the displacement deformation by 5aCAE with 2704 source nodes and ABAQUS with 1,125,833 nodes. The result is almost same with each other, and the maximum difference of displacement is only 0.66 %. In summary, this example fully demonstrates the correctness of our software when to solve the complex unilateral crack structures.

4.6. Multi-domain problem

There are 8 subdomains in the multi-domain model, its geometric model and boundary conditions are shown in Fig. 31. Automatic mesh generation is depicted in Fig. 32. Contour plots in Figs. 33,34 present the comparison of displacement and Von-Mises stress calculated by 5aCAE and ABAQUS. This example demonstrates the effectiveness and superiority of our software in dealing with practical complex problems.

4.7. Contact problem

Fig. 35 shows the contact model of semi-cylinder and cuboid and its initial discontinuous meshes. In our software, the contact area is automatically recognized without manual definition and the mesh of the contact area is automatically refined as shown in Figs. 36, 37 and 38 show the displacement and Von-Mises stress distribution of the contact area.

5. Conclusions

In this paper, the development of dual interpolation boundary face method is systematically introduced. The BFM avoids errors by geometric approximation and allows all geometric information to be taken from the entity boundary, significantly improving the computational accuracy of the BEM. Thus, the seamless connection between CAE and CAD from CAD packages to CAE calculation model can be realized. Conformal and nonconformal elements are unified due to the proposal of dual interpolation method, which enables natural simulation of continuous and discontinuous fields with the introduction of virtual nodes. Transit the evolution from DiBFM-MLS to DiBFM-HMLS, the advantage of BEM allowing for discontinuous trial functions is well exploited by dual interpolation to effectively tackle the issue of residual interpolation at small features in contemporary algorithms. To deal with the problem of singular and near-singular integrals in boundary integral equations, the spherical element subdivision method is proposed to obtain high integral precision for any kind of kernels, any element shapes and any source node locations. In terms of improving computational efficiency, the adaptive cross approximation algorithm reduces the computational complexity of the boundary element integral equation to linear or almost linear order, thus availably decrease computation time and memory usage. The dual interpolation method, combining element interpolation with meshless methods, unifies continuous and discontinuous elements, and hence makes nonconforming meshed applicable. By using a binary tree grid method, meshes with high quality can be automatically obtained for any complex structures, even CAD models with geometric noise (geometry repaired and simplification is avoided), therefore significantly alleviate the meshing task. The entire research has formed a complete and complementary theoretical system, which has been integrated into the "5aCAE simulation software".

Contrast to current commercial software, this software is explicitly on the basis of BEM and implements innovation in part theory and mesh algorithm. In addition, the software has several other advantages such as simplicity of operation, absence of abstract elements, and CAD/CAE integration etc. At present, the "5aCAE simulation software" can effectively solve problems such as elastostatics, steady heat conduction, transient heat conduction, crack growth, acoustics. The following work on fast algorithm and CPU/GPU parallel computing are expected to find applications in aerospace, marine and vehicle engineering.

CRediT authorship contribution statement

Rongxiong Xiao: Writing – original draft, Methodology, Investigation, Data curation. **Chong Zhang:** Writing – review & editing, Validation, Methodology. **Fengling Zhou:** Writing – review & editing, Visualization, Validation, Supervision. **Baotao Chi:** Writing – review & editing, Validation, Supervision. **Jianming Zhang:** Supervision, Software, Resources, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Jianming Zhang reports financial support was provided by National Natural Science Foundation of China. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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