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Overview of advanced numerical methods classified by operation dimensions

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In this article, the progress of frequently used advanced numerical methods is presented. According to the discretisation manner and manipulation dimensionality, these methods can be classified into four categories: volume-, surface-, line-, and point-operations–based methods. The volume-operation–based methods described in this article include the finite element method and element differential method; the surface-operation–based methods consist of the boundary element method and finite volume method; the line-operation–based methods cover the finite difference method and finite line method; and the point-operation–based methods mainly include the mesh free method and free element method. These methods have their own distinctive advantages in some specific disciplines. For example, the finite element method is the dominant method in solid mechanics, the finite volume method is extensively used in fluid mechanics, the boundary element method is more accurate and easier to use than other methods in fracture mechanics and infinite media, the mesh free method is more flexible for simulating varying and distorted geometries, and the newly developed free element and finite line methods are suitable for solving multi-physics coupling problems. This article provides a detailed conceptual description and typical applications of these promising methods, focusing on developments in recent years.

Keywords: finite element method, finite volume method, boundary element method, mesh free method, free element method, finite line method

INTRODUCTION

Most engineering problems can be represented by a set of second-order partial differential equations (PDEs) with relevant boundary conditions (B.C.), named the boundary value problem (BVP) of PDEs [1, 2]. For example, in thermal engineering, the diffusion-convection problem usually has the following BVP [3]:

$$\text{PDE: } \frac{\partial}{\partial x_i}\left(\lambda_{ij}(\boldsymbol{x})\frac{\partial T(\boldsymbol{x})}{\partial x_j}\right) + \frac{\partial \rho c v_i(\boldsymbol{x}) T(\boldsymbol{x})}{\partial x_i} + Q(\boldsymbol{x}) = 0,\ \boldsymbol{x} \in \Omega \tag{1}$$

$$\text{B.C.: } \begin{cases} T(\boldsymbol{x}) = \bar{T}(\boldsymbol{x}), & \boldsymbol{x} \in \Gamma_1 \\ -\lambda_{ij}(T,\boldsymbol{x})\dfrac{\partial T(\boldsymbol{x})}{\partial x_j} n_i(\boldsymbol{x}) = q(\boldsymbol{x}), & \boldsymbol{x} \in \Gamma_2 \\ -\lambda_{ij}(T,\boldsymbol{x})\dfrac{\partial T(\boldsymbol{x})}{\partial x_j} n_i(\boldsymbol{x}) = h(\boldsymbol{x})(T(\boldsymbol{x}) - T_\infty), & \boldsymbol{x} \in \Gamma_3 \end{cases} \tag{2}$$

where T is the temperature, λ_{ij} the conductivity tensor, Q the heat source, v_i the velocity, q the specified heat flux, and h the heat transfer coefficient.

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