Strategies in Edge Plasma Simulation Using Adaptive Dynamic Nodalisation Techniques

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Abstract. A wide span of steady-state and transient edge plasma processes simulation problems require accurate discretization techniques and can then be treated with Finite Element (FE) and Finite Volume (FV) methods. The software used here to meet these meshing requirements is a 2D finite element grid generator. It allows to produce adaptive unstructured grids taking into consideration the flux surface characteristics. To comply with the common mesh handling features of FE/FV packages, some options have been added to the basic generation tool. These enhancements include quadrilateral meshes without non-regular transition elements obtained by substituting them by transition constructions consisting of regular quadrilateral elements. Furthermore triangular grids can be created with one edge parallel to the magnetic field and modified by the basic adaptation/realignment techniques. Enhanced code operation properties and processing capabilities are expected.

1. Introduction

Edge plasma processes are extremely challenging problems in computer simulations. The primary reason for this is the wide range of both the time and space scales intrinsic to the behavior of fusion plasmas. Fluid modeling of the scrape-off layer (SOL) or if necessary of the entire poloidal cross section of the reaction torus is performed using a group of interconnected mesh generation tools. Although the focus of this work is on tokamak research, comparable grid specifications are encountered in solar physics and - more closely related to the problems treated here - in stellarator physics as well as inertial confinement fusion experiments [1]. In more detail the Iterative Alignment/Adaptation/Realignment (IAAR) algorithms are described here, which are based upon unstructured grids applied to the complex geometry and magnetic field structure of ITER like tokamaks.

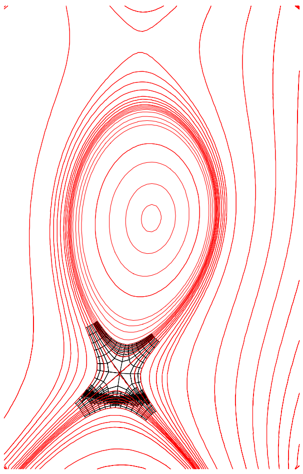

Fig. 1 Configuration of the magnetic field and meshed region

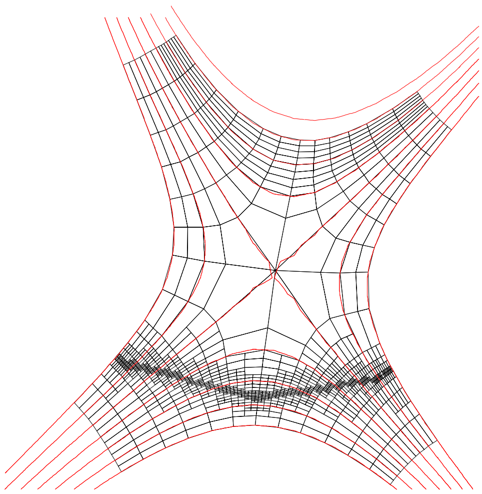

Fig. 2 Aligned and adapted grid near the X-Point

A wide span of steady-state and transient problems requiring accurate discretization techniques can be treated this way, like the propagation of sharp fronts or abrupt changes of properties, typically associated with essential radiation, ionization, and recombination processes or bifurcation paths found in the radial temperature/density profiles of regimes with internal transport barriers [2].

The basic software is a 2D finite element mesh generator which allows to produce adaptive unstructured grids taking into consideration the flux surface characteristics. The majority of the existing Finite Volume (FV) codes make use of structured grids, but some more recent developments utilize adaptive unstructured grids. These are most suitable for applying both Finite Element (FE) and FV methods as well [3].

The use of such unstructured grids is also envisaged in new software written for the geometrically complex stellarators. As the fundamental input any Grad-Shafranov solver or experimental results may deliver MHD-psi values associated with a rectangular lattice.

To a large extent the initial mesh is generated automatically and it can be adapted with interactive generator extensions to the intentions of the user. Quadrilateral elements are used in the basic tool with each two of their corresponding edges following approximately equipotential lines and lines of slope. This alignment procedure respects the extreme anisotropy of plasma transport coefficients along and perpendicular to the magnetic field [4]. E.g. in the case of electron thermal diffusion improper alignment causes a contamination of the perpendicular diffusive transport by the dominant parallel diffusive transport [5]. Compliance with element-connectivity-requirements of various solvers can be achieved, like the MIT solver requires that every element edge can border to a maximum of two adjacent elements edges [6]. This feature in turn creates a propagation effect in both the cases of refinement and coarsening. Elements which violate the connectivity condition mentioned have to be adapted.

The configuration of equipotential lines change in case of variations of the magnetic field in the space as well as in the time domain. These perturbations result in a lack of the high level of mesh alignment received in the preceding time step and some effort is taken to restore proper adaptation and alignment without the need to repeat the whole mesh generation process. Different methods of realignment are applied for this purpose: The strategies depend on the velocity of change with time of the magnetic field in relation to the travelling speed of front transition, the front's angle relative to the equipotential lines and the before/after displacements of the moved lines in relation to the local element length. The entire process cannot be restricted to fixed sub-domains since all nodes positioned originally on one single equipotential line must end up on the very same or a different line after realignment.

To comply with the common mesh handling features of FE/FV packages, some variants have been added as a first step to the basic generation tool. These enhancements include quadrilateral meshes without non-regular transition elements by substituting them by transition constructions consisting of regular quadrilateral elements. Furthermore triangular grids can be created with one side parallel to the magnetic field and modified by the basic adaptation/realignment techniques. These modifications are described in detail in the following, showing examples as appropriate.

2. Purely quadrilateral grid avoiding transition elements and intermediate nodes

Special quadrilaterals with intermediate nodes up to one at any element edge as required are used today for modeling unstructured quadrilateral grid transition zones between regions of different refinement levels. Provisions for accurate and stable numerical treatment of these transition elements is one major problem of adaptive grid schemes actually in use [7].
Even if this is done in a satisfactory way, the adaptive algorithm becomes dependent on the specific numerical method used. Furthermore, extensions of the plasma physics handled may cause changes in the treatment of transition elements too.
Therefore it would be desirable indeed to produce meshes avoiding intermediate nodes. For this reason we intend to modify the code in order to replace transition elements by structures of simple quadrilateral elements. Subdividing a quadrilateral element into a simpler one is sensitive to the number of edges with mid-edge nodes. Especially the case of an element with one intermediate edge-node remains to be solved adequately.
Unfortunately there is no way to divide such an element into quadrilaterals without generating new intermediate nodes. In „the worst case„ refinement must proceed by subdividing all adjacent elements until the boundary of the area meshed is reached.
In case there are a number of neighboring elements of this kind, especially at longer boundaries between regions of different refinement levels, then elements can be transformed two by two into 6 simple quadrilaterals see above. Special choice of the newly generated internal nodes may enable the connection of two one-intermediate-node-elements or at least diverting the subdivision propagation to the closest boundary.
We assume that alignment for the major part - but not for all - of the new elements can be achieved by applying these strategies. Some elements turn out unaligned or their angles are far from rectangular. Further adaptation of the mesh in these zones is therefore most likely to cause serious problems. Our approach to solve these problems will be to develop and employ a strategy not to refine/coarsen these elements, but to return to the 'parent' mesh (the mesh obtained by the algorithms as in the item above) that still includes the transition elements. The elements of the parent grid at the same location replace the new elements flagged for subdividing. Iterative alignment /adaptation/ realignment should be done to the parent grid and then the algorithms mentioned produce a simple quadrilateral grid.
The results of this process are representations of presumptive transient behavior as the examples shown here. Assuming a situation like in *Fig. 1.* and *Fig. 2.*, the detail of the mesh is shown in *Fig. 3.*:

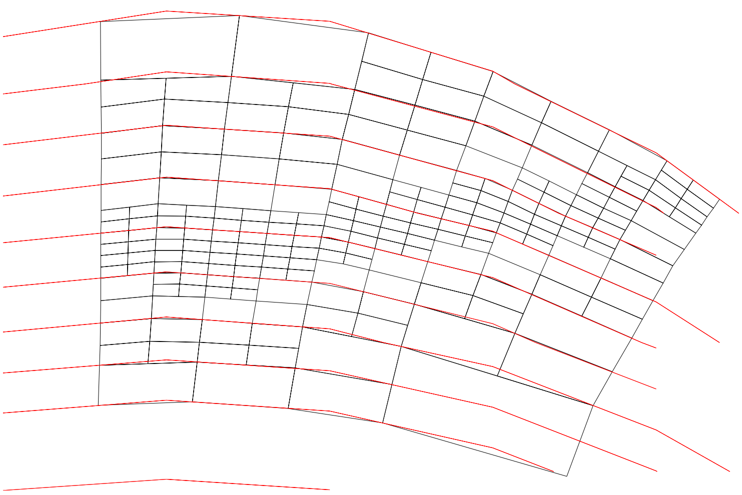

Fig. 3 Parent grid - Detail of the grid in Fig. 2

Employing the newly developed mesh manipulation strategies mentioned above, a purely quadrilateral grid (*Fig. 4*.) or a purely triangular grid (*Fig. 5*.) - depending on which sort of mesh the solver can handle - is derived from this ‘parent grid’.

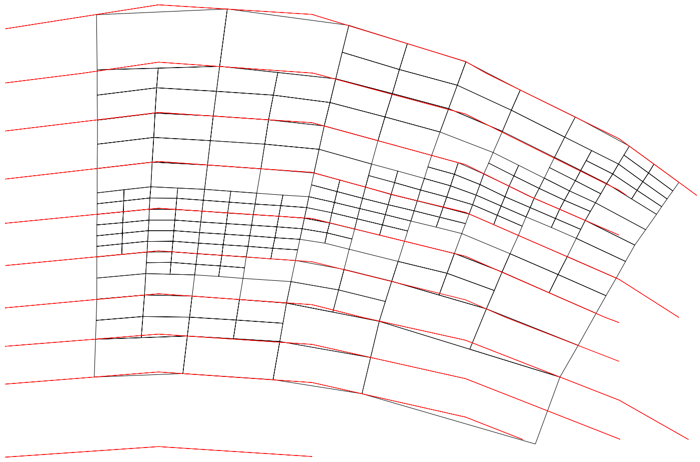

Fig. 4 Purely quadrilateral grid derived from the parent grid

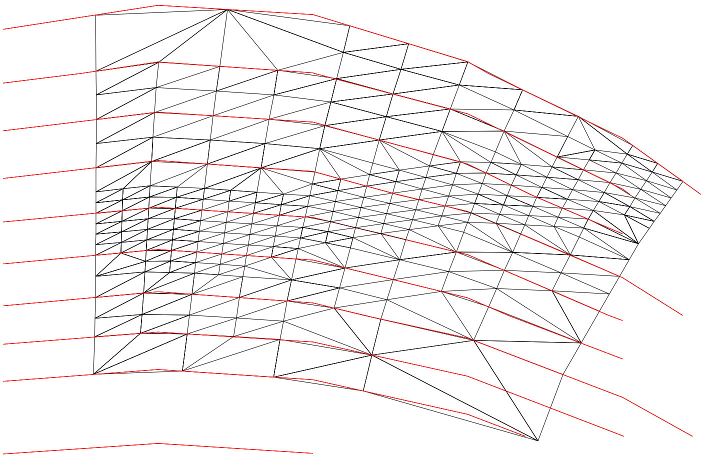

Fig. 5 Purely triangular grid derived from the parent grid

At the next time step the front has moved to the position of *Fig. 6*., captured by iterative alignment /adaptation/ realignment done on the parent mesh.

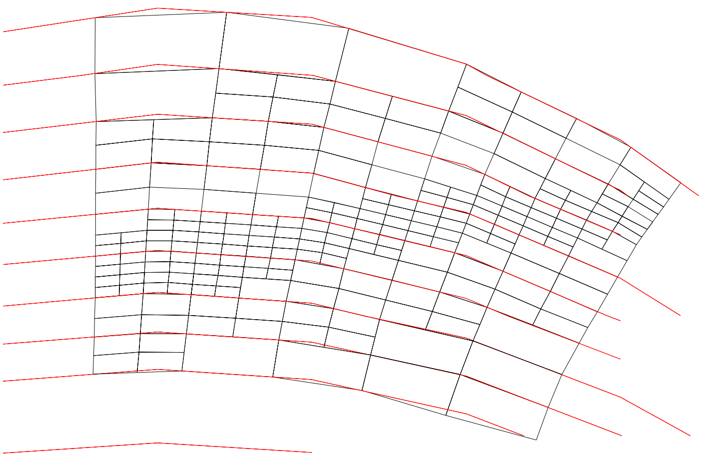

Fig. 6 Parent grid adapted to the moved front

From this new parent grid the new purely quadrilateral grid (*Fig. 7*.) or purely triangular grid

(*Fig. 8.*) is derived in the same way as done with the first parent grid.

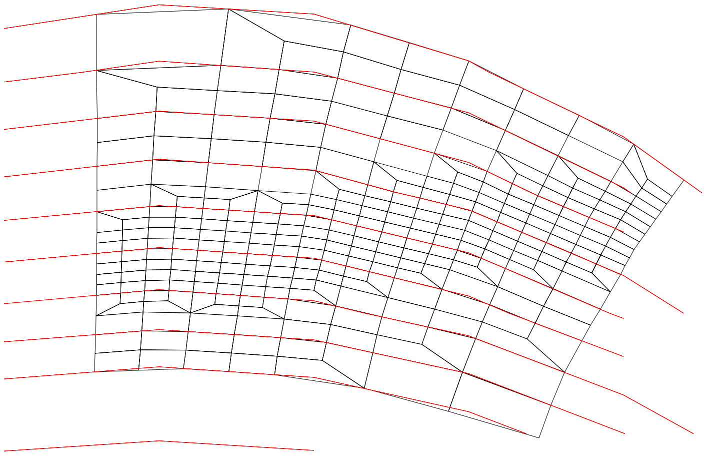

Fig. 7 Purely quadrilateral grid derived from the parent grid adapted to moved front

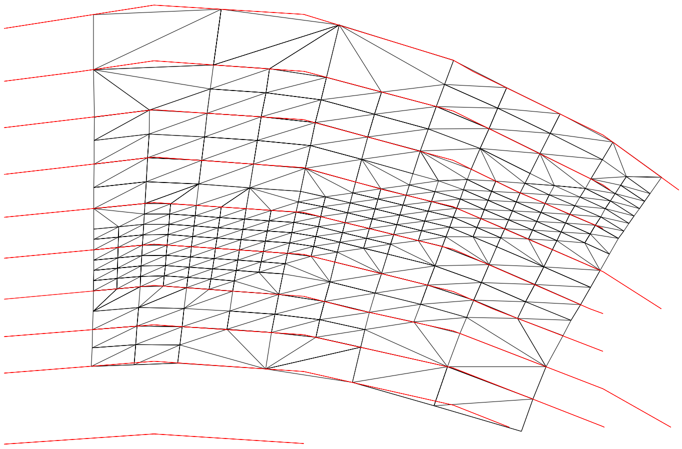

Fig. 8 Purely triangular grid derived from the parent grid adapted to the moved front

From the users point of view the parent mesh remains invisible and the connected solver deals only with a purely quadrilateral (or triangular) grid, avoiding in this way all the problems of transition elements.

3. Restrictions

The mesh generation process described is done half-automatically at this time. Figures are extrapolations of what will probably happen after connecting our code to a common fluid code. This will be set up in a project under preparation.

References

[1] J.M.Scott, J.B.Beck, Session BP1, EPS-Conference (1999)
[2] W.Horton, T.Tajima, P.Zhu, L.Leonard, Fusion Energy Sciences, Annual Report (1998)
[3] F. Subba, R. Zanino, Journal of Nuclear Materials 290-293, 743-747, (2001)
[4] A. Kainz, G. Weimann, G. Kamelander, O.V. Batishchev, APS Centennial Meeting (1999)
[5] R.Marchand, M.Simard, Nuclear Fusion, Vol. 37, No. 11, (1997)
[6] O.V. Batishchev, Contrib. Plasm.Phy. 38, (1998)
[7] K. Nakajima, Y. Kallinderis, Computer Assisted Mechanics and Engineering Sciences, Vol. 1, 123-146, (1994)

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