Adaptivity in CEA’s Fluid Elements in EUROPLEXUS

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1. Introduction

This report is a sequel to reports and publications [1-13] on mesh adaptivity in fast transient dynamics and presents the implementation of mesh adaptivity for CEA’s fluid elements (triangles and quadrilaterals in 2D, tetrahedra and hexahedra in 3D) in fast transient dynamics. The algorithms are implemented in the EUROPLEXUS code.

EUROPLEXUS [14] is a computer code for fast explicit transient dynamic analysis of fluid-structure systems jointly developed by the French Commissariat à l’Energie Atomique et aux Energies Alternatives (CEA Saclay) and by the Joint Research Centre of the European Commission (JRC Ispra).

Reference [1] presented the first implementation in EUROPLEXUS of an adaptive mesh refinement and un-refinement procedure, in two space dimensions (element shape QUA4) for solid mechanics. The procedure was extended to fluid mechanics (FE formulation) in 2D in reference [2]. Then, reference [3] applied a similar refinement and un-refinement procedure in three space dimensions to the CUB8 element shape, both in solids mechanics and in fluid mechanics (FE formulation).

All numerical examples presented in references [1-3] with a variable mesh used a so-called “manual” mesh adaptation directive, the WAVE directive (see the code manual in reference [14]), first introduced in reference [1]. This directive refines the mesh along “wavefronts” that are specified by the user, e.g. according to a known analytical solution to the problem considered. This technique was used with success to simulate a bar problem (in solid mechanics) and a shock tube problem (in fluid mechanics) both in 2D and in 3D [1-3].

However, those solutions cannot be qualified as “true” adaptive solutions, because in (true) adaptivity mesh refinement and un-refinement should be completely automatic, based upon suitable error estimators or error indicators. The formulation of error estimators in fast transient dynamics is challenging and is still a subject of research. The use of so-called error indicators, however, is much simpler. For this reason, subsequent work in EUROPLEXUS focused on error indicators. References [4] and [5] document a first prototype implementation of adaptivity based upon error indicators in EUROPLEXUS, limited to 2D problems in continuum and fluid mechanics. An extension of the indicator technique to 3D is under development but has not been completed and documented yet.

Publications [6-7] focus on the natural quantities of interest in goal-oriented error assessment and adaptivity, but limited to the case of linear elasto-dynamics.

The adaptive technique was then applied to Cell-Centred Finite Volumes (CCFV) for the description of the fluid domain, first in 2D (see [8]) and then also in 3D [9]. More recently, the technique has also been extended for use with the CDEM combustion model which makes use of the CCFV formulation [10]. A complete description of the element refinement and un-refinement techniques used in
mesh adaptation has been published in a paper [11]. Finally, reference [12] shows the combination of mesh adaptivity with Fluid-Structure Interaction, i.e. the automatic fluid mesh refinement and un-refinement near a moving and deforming structure.

Reference [13] extends mesh adaptivity to simplex element shapes, i.e. the 3-node triangle (TRI3) in 2D and the 4-node tetrahedron (TET4) in 3D. These elements are useful in fully general unstructured meshing of complex geometries. The extension covered solid continuum elements (CEA’s TRIA and TETR elements with solid material), and for fluid Finite Elements (JRC’s FL23 and FL34 elements) and Cell-Centered Finite Volumes (CEA’s T3VF and TEVF elements).

The present work completes the implementation by extending adaptivity to CEA’s fluid finite elements both in 2D (TRIA and CAR1) and in 3D (TETR and CUBE). The CAR1 is treated like other 2D quadrilaterals (Q41L, FL24) as far as geometrical issues are concerned. In addition to the solid case, the activation of adaptivity for fluids requires the suitable treatment of transport terms which arise in the Eulerian or ALE forms of the governing equations. For the CEA’s fluid finite elements mentioned above (TRIA, CAR1, TETR and CUBE) this is done in routines tr2me.ff (for the 2D case) and tr3me.ff (for the 3D case), respectively. Therefore, most modifications for the current implementation are concentrated in those two routines. Actually, a special version of the routines is written, valid for the mesh adaptive case, but incompatible (for the moment) with the KAAPI library and with spatial partitioning, in order to limit the complexity of the resulting code.

This document is organized as follows:

- Section 2 presents the treatment of transport terms.
- Section 3 presents some numerical examples with 2D fluid elements (TRIA, CAR1).
- Section 4 presents some numerical examples with 3D fluid elements (TETR, CUBE).
- The references are listed in Section 5.

The Appendix contains a listing of all the input files mentioned in the present report.
2. Treatment of transport terms in adaptivity for CEA’s fluid FEs

The CEA implementation of fluid Finite Elements differs somewhat from the one of JRC similar elements, that had been described e.g. in Section 2.2 of reference [2]. The conservation equations (Euler equations) are the same in both cases, of course, but CEA’s approach is to use the same element routine for both solid and fluid, and to treat the transport terms in a separate routine (tr2me.ff for the 2D case and tr3me.ff for the 3D case). These routines compute the mass and energy transport terms across each face of the fluid elements. Faces are 2-node segments in 2D, and either 3-node triangles or 4-node quadrilaterals in 3D.

Although there are differences with respect to JRC’s implementation, the key point is that in both cases the so-called “lowest-index rule” is used when computing transport between two neighboring elements, see Section 2.2.3 of reference [2]. Therefore, in CEA’s fluid elements a similar extension to the adaptive case can be applied to the one adopted in JRC case and described in detail in Section 2.3 of reference [2].

This extension is based upon the generalization of “neighbor” definition and on the addition of a “pseudo-neighbor” definition, which applies to portions of the fluid-fluid interfaces which are non-conforming due to the presence of so-called hanging nodes in an adaptively refined mesh. These definitions are recalled below, see also the Figure 1 from reference [2].

**Definition of (regular) neighbor element in adaptivity**

The neighbor of an element across a given face is the same-level, active or inactive element on the other side of the face, or 0 if there is no such element.

**Definition of pseudo-neighbor element in adaptivity**

The pseudo-neighbor of an (active) element across a given face is the larger (i.e. lower-level) active element on the other side of the face, or 0 if there is no such element. Inactive elements have no pseudo-neighbors.

![Figure 1 - Neighboring (in black) and pseudo-neighboring (in red) relations](image_url)
The generalized transport algorithm, valid both in the normal (non-adaptive) and in the adaptive case, can therefore be reused as such from Section 2.3.5 of reference [2], also in the case of CEA’s fluid elements. The algorithm is reported below for completeness.

**General (non-adaptive or adaptive) transport algorithm**

1. Set total transport of mass and energy to zero for all elements.
2. Loop over the elements.
   3. Loop over the faces of the current element $i$.
      4. Let $j$ be the neighbor of $i$ across the current face.
      5. If there is no adaptivity in the calculation, then (standard procedure):
         6. If $j = 0$ (i.e., if there is no neighbor) skip transport for this face (GO TO 21).
         7. Else, if $j < i$ skip transport for this face (GO TO 21).
         8. Else $j > i$ : compute the transports of mass $\Delta M$ and of internal energy $\Delta I$ between $i$ and $j$, add them (with the correct sign) to the total transport of mass and energy of element $j$, and subtract them from the total transport of mass and energy of element $i$. Go to next face (GO TO 21).
      9. Else there is adaptivity in the calculation.
         10. If $j = 0$ (i.e. if there is no neighbor), let $k$ be the pseudo-neighbor.
             11. If $k = 0$ (i.e., if there is no pseudo-neighbor) or $k < i$, skip transport for this face (GO TO 21).
             12. Else $k > i$ : compute the transports of mass $\Delta M$ and of internal energy $\Delta I$ between $i$ and $k$, add them (with the correct sign) to the total transport of mass and energy of element $k$, and subtract them from the total transport of mass and energy of element $i$. Go to next face (GO TO 21).
      13. Else, $j > 0$ ($j$ is the neighbor of $i$ across the current face).
      14. If element $j$ is active then:
          15. If $j < i$, skip transport for this face (GO TO 21).
          16. Else $j > i$ : compute the transports of mass $\Delta M$ and of internal energy $\Delta I$ between $i$ and $j$, add them (with the correct sign) to the total transport of mass and energy of element $j$, and subtract them from the total transport of mass and energy of element $i$. Go to next face (GO TO 21).
          17. Else, $j$ is inactive. Search and loop over all active descendents $k$ of $j$ which see $i$ as pseudo-neighbor.
          18. If $k < i$, skip transport for this $k$ (GO TO 20).
          19. Else $k > i$ : compute the transports of mass $\Delta M$ and of internal energy $\Delta I$ between $i$ and $k$ by using the geometry of $k$, not of $i$, add them (with the correct sign) to the total transport of mass and energy of element $k$, and subtract them from the total transport of mass and energy of element $i$. Go to next $k$ (GO TO 20).
      20. Next $k$ (GO TO 15).
      21. Next face (GO TO 3).
      22. All faces have been considered for the current element and therefore its total transport of mass and energy has been computed. Update the element state to its final (end-of-step) value and compute internal forces.
      23. Next element (GO TO 2)
As anticipated in the Introduction, the (adaptive part of the) above algorithm is implemented in two new routines, \texttt{tr2me\_adap.ff} for the 2D case and \texttt{tr3me\_adap.ff} for the 3D case, respectively. These routines are called from the element routines whenever adaptivity is activated in a calculation, in place of the “normal” routines \texttt{tr2me.ff} and \texttt{tr3me.ff}. The separation of cases is useful to keep the algorithms readable. However, a drawback of this implementation is that adaptivity cannot be combined with the KAAPI library, nor with spatial partitioning (such cases are only treated in the normal non-adaptive version of the routines).
3. Numerical examples in 2D

We present some numerical examples in order to test the algorithms described in the previous Sections.

3.1 Shock tube in 2D

The first example is a classical shock tube, similar to those considered in reference [2]. The adaptive mesh refinement is piloted by the WAVE directive.

First, reference solutions are obtained by means of a fine mesh of (non-adaptive) triangles (TRIA) or quadrilaterals (CAR1). Then, adaptive solutions with triangles or quadrilaterals are obtained. All performed calculations are summarized in Table 1.

<table>
<thead>
<tr>
<th>Case</th>
<th>Base Mesh</th>
<th>Notes</th>
<th>Steps</th>
<th>CPU [s]</th>
<th>Els*step</th>
</tr>
</thead>
<tbody>
<tr>
<td>FETR00</td>
<td>1,600 TRIA</td>
<td>Non-adaptive fine mesh</td>
<td>1,082</td>
<td>2.5</td>
<td>1,732,800</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CSTA 0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FETR01</td>
<td>200 TRIA</td>
<td>WAVE 4 PLAN MAXL 4</td>
<td>2,279</td>
<td>7.9</td>
<td>2,865,237</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CSTA 0.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FEQU00</td>
<td>800 CAR1</td>
<td>Non-adaptive fine mesh</td>
<td>838</td>
<td>1.6</td>
<td>671,200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CSTA 0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FEQU01</td>
<td>100 CAR1</td>
<td>WAVE 4 PLAN MAXL 4</td>
<td>1,681</td>
<td>4.9</td>
<td>1,056,875</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CSTA 0.25</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1 - Calculations for the shock tube problem with 2D Finite Elements

FETR00
This test uses a fine non-adaptive fluid mesh, of \(800 \times 2 = 1600\) triangular fluid elements TRIA. To obtain a solution with relatively few oscillations near the shock front, it is necessary to add some damping: \texttt{OPTI AMOR QUAD 4 0 LINE 0.2}. The solution is shown in Figures 2 (pressure), 3 (density) and 4 (velocity). This is taken as a reference for the subsequent adaptive solution.

FETR01
This solution is adaptive and uses a coarse base fluid mesh of 200 triangles, and four WAVE directives to track the wavefronts, with a maximum refinement level \texttt{MAXL 4}. A stability coefficient of 0.25 (instead of 0.5 like in the reference case) is needed to ensure stability. The solution is shown in Figures 5 (pressure), 6 (density) and 7 (velocity) and is in reasonable agreement with the reference.

FEQU00
This test uses a non-adaptive fine fluid mesh, of 800 quadrilateral fluid elements CAR1. To obtain a solution with relatively few oscillations near the shock front, it is necessary to add some damping:
OPTI AMOR QUAD 4.0 LINE 0.2. The solution is shown in Figures 8 (pressure), 9 (density) and 10 (velocity). This is taken as a reference for the subsequent adaptive solution.

**FEQU01**
This solution is adaptive and uses a coarse base fluid mesh of 100 CAR1, and four WAVE directives to track the wavefronts, with a maximum refinement level MAXL 4. A stability coefficient of 0.25 (instead of 0.5 like in the reference case) is needed to ensure stability. The solution is shown in Figures 11 (pressure), 12 (density) and 13 (velocity) and is in reasonable agreement with the reference.
Figure 2 - Pressure in case FETR00

Figure 3 - Density in case FETR00
Figure 4 - Velocity in case FETR00

Figure 5 - Pressure in case FETR01
Figure 6 - Density in case FETR01

Figure 7 - Velocity in case FETR01
Figure 8 - Pressure in case FEQU00

Figure 9 - Density in case FEQU00
Figure 10 - Velocity in case FEQU00

Figure 11 - Pressure in case FEQU01
Figure 12 - Density in case FEQU01

Figure 13 - Velocity in case FEQU01
4. Numerical examples in 3D

We present some numerical examples in order to test the algorithms described in the previous Sections.

4.1 Shock tube in 3D

The next example is a classical shock tube, similar to those considered in reference [2]. The adaptive mesh refinement is piloted by the `WAVE` directive.

First, reference solutions are obtained by means of a fine mesh of (non-adaptive) tetrahedra (TETR) or hexahedra (CUBE). Then, adaptive solutions with tetrahedra or hexahedra are obtained. All performed calculations are summarized in Table 2.

<table>
<thead>
<tr>
<th>Case</th>
<th>Base Mesh</th>
<th>Notes</th>
<th>Steps</th>
<th>CPU [s]</th>
<th>Els*step</th>
</tr>
</thead>
<tbody>
<tr>
<td>FET400</td>
<td>1,200 TETR</td>
<td>Non-adaptive fine mesh C STA 0.5</td>
<td>237</td>
<td>0.7</td>
<td>285,600</td>
</tr>
<tr>
<td>FET401</td>
<td>1,200 TETR</td>
<td>WAVE 4 PLAN MAXL 3 CSTA 0.125</td>
<td>3,100</td>
<td>70.2</td>
<td>23,592,114</td>
</tr>
<tr>
<td>FEC800</td>
<td>100 CUBE</td>
<td>Non-adaptive fine mesh CSTA 0.5</td>
<td>119</td>
<td>0.2</td>
<td>12,000</td>
</tr>
<tr>
<td>FEC801</td>
<td>100 CUBE</td>
<td>WAVE 4 PLAN MAXL 3 CSTA 0.25</td>
<td>834</td>
<td>7.5</td>
<td>530,681</td>
</tr>
</tbody>
</table>

Table 2 - Calculations for the shock tube problem with 2D Finite Elements

**FET400**

This test uses a fine non-adaptive fluid mesh, of \(100 \times 12 = 1200\) tetrahedral fluid elements TETR. To obtain a solution with relatively few oscillations near the shock front, it is necessary to add some damping: `OPTI AMOR QUAD 4.0 LINE 0.2`. The solution is shown in Figures 14 (pressure), 15 (density) and 16 (velocity). This is taken as a reference for the subsequent adaptive solution.

**FET401**

This solution is adaptive and uses the same base fluid mesh as the previous case, and four `WAVE` directives to track the wavefronts, with a maximum refinement level `MAXL 3`. A stability coefficient of 0.125 (instead of 0.5 like in the reference case) is needed to ensure stability. The solution is shown in Figures 17 (pressure), 18 (density) and 19 (velocity) and is in reasonable agreement with the reference.
This test uses a non-adaptive fluid mesh, of 100 hexahedral fluid elements CUBE. To obtain a solution with relatively few oscillations near the shock front, it is necessary to add some damping: OPTI AMOR QUAD 4.0 LINE 0.2. The solution is shown in Figures 20 (pressure), 21 (density) and 22 (velocity). This is taken as a reference for the subsequent adaptive solution.

This solution is adaptive and uses the same base fluid mesh as the previous case, and four WAVE directives to track the wavefronts, with a maximum refinement level MAXL 3. A stability coefficient of 0.25 (instead of 0.5 like in the reference case) is needed to ensure stability. The solution is shown in Figures 23 (pressure), 24 (density) and 25 (velocity) and is in reasonable agreement with the reference.
Figure 14 - Pressure in case FET400

Figure 15 - Density in case FET400
Figure 16 - Velocity in case FET400

Figure 17 - Pressure in case FET401
Figure 18 - Density in case FET401

Figure 19 - Velocity in case FET401
Figure 20 - Pressure in case FEC800

Figure 21 - Density in case FEC800
Figure 22 - Velocity in case FEC800

Figure 23 - Pressure in case FEC801
Figure 24 - Density in case FEC801

Figure 25 - Velocity in case FEC801
5. References


[12] F. Casadei, G. Valsamos, A. Beccantini: “Combination of Mesh Adaptivity with Fluid-


Appendix

Sample input files

This Section contains, in alphabetical file order, the listings of all input files related to the examples which were proposed in the previous Sections.

---

**fec800.epx**

```plaintext
PGEO
ECHO
|CONV win
|CAST mesh
EULE TRID
NGRO 5 'xaxo' LECT bar TERM
COMP GEOM 4 'bar1' LECT 1 PAS 1 50 TERM
'bar1' LECT 1 PAS 1 100 TERM
'ea' LECT 24 TERM
LATE X MTU GRAP 10 GGAM 1.0 PINT 1.8 EQUF 1.8
LATE Y LECT bar TERM
LATE Z KO
ECHO

**fec801.epx**

```plaintext
PGEO
ECHO
|CONV win
|CAST mesh
EULE TRID
NGRO 5 'xaxo' LECT bar TERM
COMP GEOM 4 'bar1' LECT 1 PAS 1 50 TERM
'bar1' LECT 1 PAS 1 100 TERM
'ea' LECT 24 TERM
LATE X MTU GRAP 10 GGAM 1.0 PINT 1.8 EQUF 1.8
LATE Y LECT bar TERM
LATE Z KO
ECHO
```
n = 800;
tol = 1.E-5;

pb = 0.75

p1p = p1 plus (0 0.00125);

p1 = 1 0

p0p = p0 plus (0 0.00125);

p0 = 0 0

opti sauv form 'fequ00.msh';

opti echo 1;

opti donn 'pxordpoi.proc';

opti echo 0;

*=================================================================

TRAC OFFS SIZE 1400 400 FICH BMP REND

! LINE HEOU

SCEN GEOM NAVI FREE

TRAC OFFS SIZE 1400 400 FICH BMP REND

! LINE HEOU

SCEN GEOM NAVI FREE

SORT GRAP

RESU ALIC GARD PSCR

ECHO

Post-treatment (space curves from alice file)

SUIT

OPTI NOTE STEP IO

* Q 1.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00

CAME 1 EYE 5.00000E-01 5.00000E-03 3.00015E-01

SORT VISU NSTO 61

OPTI PRIN

RESU ALIC GARD PSCR

ECHO

Post treatment (BMPs from alice file)

*=================================================================

LIST 2 5 AXES 1.0 'DENS. [KG/M3]'

LIST 1 4 AXES 1.0 'PRESS. [PA]'

COLO NOIR NOIR

COLO NOIR NOIR

TRAC 2 5 AXES 1.0 'DENS. [KG/M3]'

COLO NOIR NOIR

TRAC 1 4 AXES 1.0 'PRESS. [PA]'

COUR 6 'vx_eb' VITE COMP 1 NOEU LECT nb TERM

COUR 5 'ro_eb' ECRO COMP 2 ELEM LECT eb TERM

COUR 4 'p_eb' ECRO COMP 1 ELEM LECT eb TERM

COUR 1 'p_ea' ECRO COMP 1 ELEM LECT ea TERM

PERF 'fec801t.pun'

SORT GRAP

RESU ALIC TEMP GARD PSCR

ECHO

Post-treatment (time curves from alice temps file)

SUIT

QUAL ECRO COMP 1 LECT ea TERM REFE 9.97352E+5 TOLE 2.E-2

* LIST 65 AXES 1.0 'VELOC. [M/S]'

COLO NOIR VERT

LIST 62 AXES 1.0 'DENS. [KG/M3]'

COLO NOIR VERT

LIST 61 AXES 1.0 'PRESS. [PA]'

COLO NOIR VERT

TRAC 61 71 AXES 1.0 'PRESS. [PA]'

DCOU 75 'v_ana' SHTU GAMM 1.5 ROM 10 ROP 1 EINT 2.0E5 LENM 0.5 LENP 0.5

DCOU 72 'r_ana' SHTU GAMM 1.5 ROM 10 ROP 1 EINT 2.0E5 LENM 0.5 LENP 0.5

SCOU 62 'ro_61' NSTO 61 SAXE 1.0 'curr_abscissa' LECT xaxo TERM

LOG 1

AMOR QUAD 4.0 LINE 0.2

FICH ALIC TEMP FREQ 1

COLO PAPE

TEXT ISCA

ISO FILL FIEL VITE SCAL USER PROG 20 PAS 20 280 TERM

FICH ALIC TFRE 1.0E-5

ECRO COMP 2 LECT eb TERM REFE 2.02291E+0 TOLE 2.E-2

FOV 5.25000E+01

UP 0.00000E+00 1.00000E+00 0.00000E+00

RIGH 1.00000E+00 0.00000E+00 0.00000E+00

VIEW 0.00000E+00 0.00000E+00 -1.00000E+00

BLOQ 23 LECT bar TERM

POIN LECT na nb TERM

TIME 0.60E-3 NRAR 30 VARI 1

TIME 0.60E-3 NRAR 30 VARI 2

VITE COMP 1

ECRO COMP 2

TIME 0.60E-3 NRAR 30 VARI 5

VITE COMP 1

ECRO COMP 2

TIME 0.60E-3 NRAR 30 VARI 5

TRAC 61 71 AXES 1.0 'PRESS. [PA]'

COLO NOIR VERT

TRAC 65 75 AXES 1.0 'VELOC. [M/S]'

LIST 62 AXES 1.0 'DENS. [KG/M3]'

COLO NOIR VERT

TRAC 62 72 AXES 1.0 'DENS. [KG/M3]'

LIST 61 AXES 1.0 'PRESS. [PA]'

COLO NOIR VERT

TRAC 61 71 AXES 1.0 'PRESS. [PA]'

DCOU 75 'v_ana' SHTU GAMM 1.5 ROM 10 ROP 1 EINT 2.0E5 LENM 0.5 LENP 0.5

DCOU 71 'p_ana' SHTU GARD 1.0 R INT 2.0E5 LEXN 0.5 LEPN 0.5

ABS 5 19 April 2014 4:58 pm

fin;
### fequ01.epx

**LIST 65 AXES 1.0 'VELOC. [M/S]'**

**TRAC 65 75 AXES 1.0 'VELOC. [M/S]'**

**LIST 61 AXES 1.0 'PRESS. [PA]'**

**DCOU 72 'r_ana' SHTU GAMM 1.5 ROM 10 ROP 1 EINT 2.0E5 LENM 0.5 LENP 0.5**

**SCOU 61 'p_61' NSTO 61 SAXE 1.0 'curr_abscissa' LECT xaxo TERM**

*En general, il est toujours une bonne idee de specifier le SUPPort,*

**AXTE 1.0 'Time [s]'**

**!PERF 'fequ01.pun'**

**MATE GAZP RO 10 GAMM 1.5 PINI 1.E6 PREF 1.E5**

**COMP GROU 5 'bar1' LECT 100 TERM**

**ECRO COMP 2 LECT ea TERM REFE 9.99666E+0 TOLE 2.E-2**

**ECRO COMP 1 LECT eb TERM REFE 2.84565E+5 TOLE 2.E-2**

**FICH ALIC TFRE 1.0E-5**

**GAZP RO 1 GAMM 1.5 PINI 1.E5 PREF 1.E5**

**NGRO 7 'p0' LECT 1 TERM**

**PLAN X 0.5 Y 0 NX -1 NY 0 T0 0 C 387.298334620742 ! r. wave (left)**

**MAXL 4 H1 0.015 H2 0.05**

**AMOR QUAD 4.0 LINE 0.2**

**CALC TINT 0. TEMD 0.068-**

**SUIT**

**FEQ01**

**EQU**

**!CIV win**

**Rolle SPAL**

**DIME**

**ALAD EROI 3000 3150 2000 E20A**

**TRM**

**GEO**

**LIBR POI 202 CAR1 100 TERM**
fet400.dgibi

19 April 2014 4:58 pm

Post treatment (BMPs from alice file)
ECRO
RESU ALIC GARD GRSCH
OPTI FIN
SORT VISU MUTO 41
PLAY
CAME 1 EYE 5.00000E-01 5.00000E-03 3.00015E-01
! 0 1 0 0 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00
VIEW 0.00000E+00 0.00000E+00 -1.00000E+00
SIZE 1.00000E+00 1.00000E+00 1.00000E+00
UP 1.00000E+00 1.00000E+00 1.00000E+00
F24.00000E+01
SCEN GEOM NAVI FREE
LINE MEEO
ISO FILL PIEL VITE SCAI USER PROG 20 PAS 20 280 TERM
SUPP LECT bar TERM
TEXT ISCA
COLO PAPA
SLER CAM1 1 NFRA 1
TRAC OFFS SIZE 1400 400 FICH BMP REND
SLER CAM1 1 NFRA 1
TRAC OFFS SIZE 1400 400 FICH BMP REND
TRAC OFFS SIZE 1400 400 FICH BMP REND
ENDPLAY

fet400.epx

PFT400
ECRO
!COMP win
CAST mesh
EVAL TRIS
GEOM TRIS bar TERM
COMP GEOS 4 'bar1' LECT bar TERM COMD XG LT 0.5
'bar1' LECT bar DIFF bar1 TERM
'as' LECT bar TERM COMD NEAR POIN 0.25 0 0
'ab' LECT bar TERM COMD NEAR POIN 0.75 0 0
SUBG 5 'asaxo' LECT bar TERM COMD LINE XI 0 Y1 0 Z1 0
X2 1 Y2 0 Z2 0 TOL 1.E-4
'asaxo' LECT bar TERM COMD XI 0.0001
'basax' LECT bar TERM COMD XG OT 0.9999
'na' LECT bar TERM COMD NEAR POIN 0.25 0 0
'nh' LECT bar TERM COMD NEAR POIN 0.75 0 0
COUL ROUG LECT bar TERM
VEST LECT bar TERM
NATR GEOS 10.0 GANN 1.0 PINT 1.64 PREP 1.95 LECT bar TERM
GADD 1.0 GANN 1.0 GAST 1.95 PREP 1.95 LECT bar TERM
LINK GEOS 1 LECT bar1 LECT bar2 LECT bar3 LECT bar4 LECT bar5 LECT bar6 LECT bar7 LECT bar8 LECT bar9 LECT bar0 LECT bar1
ECRO COMD CURL VITE ACCE PINT FEXT CURG VVCY VYCY TYPE 0.3E-3
PINC ALIC TYPE FREQ 1
PINC LECT na ah TERM
ELMEN LECT ex ah TERM
PINC ALIC TYPE 0.1E-5
OPTI NUTE STEP TO
AMEX QUAD 4.0 LUNE 0.2
CRES 0.8
LOG 0
CALC TART 0. TEND 0.450.3

**Post treatment (space curves from alice file)**
ECRO
RESU ALIC GARD GRSCH
SORT GRAP

fet401.dgibi

opti echo 1;
opti donn 'pgeahezte.proc';
opti dize 3 eles cubi;
opti titr 'PFT401';
opti sauw form 'fet401.mah';
opti trac per ftra 'fet401_mesh.pas';
p0 = 0 0 0;
s0 = 0.1;
tol = 0.0001;
p1 = 0 d0 0;
p2 = 0 d2 0;
p3 = 0 dd 0;
c1 = p0 d1 p1;
c2 = p1 d1 p2;
c3 = p2 d1 p3;
c4 = p3 d1 p4;
bas = dail c1 c2 c3 c4 c5 p0 p1 p2 p3 p4;
bar = base volu n tran ((n*dd) 0 0 0);
"id = 0;
repe loop1 (nbel bar8);
i=0;
base = dall c1 c2 c3 c4 plan;
c 4=p 3d1p 0 ;
c 2=p 1d1p 2 ;
c 1=p 0d1p 1 ;
p2 = 0 d2 dd;
p1 = 0 dd dd;
p0 = 0 dd 0;
tol = 0.0001;
n = 100;
p0 = 0 0 0;
opti sauv form 'fet401.msh';
opti titr 'FET401';
opti donn 'pxhex2te.proc';
opti echo 1;

*=================================================================

fet400.epx

PFT400
ECRO
!COMP win
CAST mesh
EVAL TRIS
GEOM TRIS bar TERM
COMP GEOS 4 'bar1' LECT bar TERM COMD XG LT 0.5
'bar1' LECT bar DIFF bar1 TERM
'as' LECT bar TERM COMD NEAR POIN 0.25 0 0
'ab' LECT bar TERM COMD NEAR POIN 0.75 0 0
SUBG 5 'asaxo' LECT bar TERM COMD LINE XI 0 Y1 0 Z1 0
X2 1 Y2 0 Z2 0 TOL 1.E-4
'asaxo' LECT bar TERM COMD XI 0.0001
'basax' LECT bar TERM COMD XG OT 0.9999
'na' LECT bar TERM COMD NEAR POIN 0.25 0 0
'nh' LECT bar TERM COMD NEAR POIN 0.75 0 0
COUL ROUG LECT bar TERM
VEST LECT bar TERM
NATR GEOS 10.0 GANN 1.0 PINT 1.64 PREP 1.95 LECT bar TERM
GADD 1.0 GANN 1.0 GAST 1.95 PREP 1.95 LECT bar TERM
LINK GEOS 1 LECT bar1 LECT bar2 LECT bar3 LECT bar4 LECT bar5 LECT bar6 LECT bar7 LECT bar8 LECT bar9 LECT bar0 LECT bar1
ECRO COMD CURL VITE ACCE PINT FEXT CURG VVCY VYCY TYPE 0.3E-3
PINC ALIC TYPE FREQ 1
PINC LECT na ah TERM
ELMEN LECT ex ah TERM
PINC ALIC TYPE 0.1E-5
OPTI NUTE STEP TO
AMEX QUAD 4.0 LUNE 0.2
CRES 0.8
LOG 0
CALC TART 0. TEND 0.450.3

**Post treatment (space curves from alice file)**
ECRO
RESU ALIC GARD GRSCH
SORT GRAP

fet401.dgibi

opti echo 1;
opti donn 'pgeahezte.proc';
opti dize 3 eles cubi;
opti titr 'PFT401';
opti sauw form 'fet401.mah';
opti trac per ftra 'fet401_mesh.pas';
p0 = 0 0 0;
s0 = 0.1;
tol = 0.0001;
p1 = 0 d0 0;
p2 = 0 d2 0;
p3 = 0 dd 0;
c1 = p0 d1 p1;
c2 = p1 d1 p2;
c3 = p2 d1 p3;
c4 = p3 d1 p4;
bas = dail c1 c2 c3 c4 c5 p0 p1 p2 p3 p4;
bar = base volu n tran ((n*dd) 0 0 0);
"id = 0;
repe loop1 (nbel bar8);
i=0;
base = dall c1 c2 c3 c4 plan;
c 4=p 3d1p 0 ;
c 2=p 1d1p 2 ;
c 1=p 0d1p 1 ;
p2 = 0 d2 dd;
p1 = 0 dd dd;
p0 = 0 dd 0;
tol = 0.0001;
n = 100;
p0 = 0 0 0;
opti sauv form 'fet401.msh';
opti titr 'FET401';
opti donn 'pxhex2te.proc';
opti echo 1;

*=================================================================

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**fet401.epx**

ECHO

CAST mesh

ECHO

fet401.epx

fin;

sauv form mesh;

msh = bar _tetr TERM

 COMP GROU 4 'bar1' LECT bar TERM COND XB LT 0.5

'bar1' LECT bar DIFF bar TERM

'ea' LECT bar TERM COND NEAR POIN 0.25 0 0

'ab' LECT bar TERM COND NEAR POIN 0.75 0 0

maxl 3 H1 0.015 H2 0.05

maxl 3 H1 0.015 H2 0.05

maxl 3 H1 0.015 H2 0.05

MAXI GAP 10 GANN 1.5 PINI 1.40E+00 PREF 1.0E4

LECT bar TERM VERT LECT bar TERM

MATE GAZP RO 10 GAMM 1.5 PINI 1.0E6 PREF 1.0E5

ECRI COOR DEPL VITE ACCE FINT FEXT CONT ECRO TFRE 0.3E-3

WAVE 4 PLAN X 0.5 Y 0 Z 0 NX 1 NY 0 NZ 0 T0 0 C 631.54875989856 ! shock wave

MAXI 3 H1 0.015 H2 0.05

PLAN X 0.5 Y 0 Z 1 NY 0 NZ 0 C 18.200470934493 ! c.d. wave

PLAN X 0.5 Y 0 Z 1 NY 0 NZ 0 C 295.275820934493 ! c.d. wave

PLAN X 0.5 Y 0 Z 0 T0 0 C 347.298334620742 ! r. wave

> CALC TINI 0. TEND 0.50E-3

PLAY

*=================================================================

CALC TINI 0. TEND 0.60E-3

SORT VISU NSTO 61

OPTI PRIN

RESU ALIC GARD PSCR

Post-treatment (BMPs from alice file)

COLO NOIR NOIR

TRAC 3 6 AXES 1.0 'VELOC. [M/S]' DIFF bar TERM

CORR 6 'vx_eb' VITE COMP 1 NOEU LECT nb TERM

CORR 5 'ro_ea' ECRO COMP 2 ELEM LECT ea TERM

CORR 4 'p_ea' ECRO COMP 1 ELEM LECT ea TERM

CORR 3 'vx_ea' VITE COMP 1 NOEU LECT na TERM

CORR 2 'ro_ea' ECRO COMP 2 ELEM LECT ea TERM

CORR 1 'p_ea' ECRO COMP 1 ELEM LECT ea TERM

PERF 'fet401t.pun'

SORT GRAP

RESU ALIC TEMP GARD PSCR

ECHO

Post-treatment (time curves from alice temps file)

LIST 65 AXES 1.0 'VELOC. [M/S]'

LIST 62 AXES 1.0 'DENS. [KG/M3]'

LIST 61 AXES 1.0 'PRESS. [PA]'

DCOU 75 'v_ana' SHTU GAMM 1.5 ROM 10 ROP 1 EINT 2.0E5 LENM 0.5 LENP 0.5

DCOU 72 'r_ana' SHTU GAMM 1.5 ROM 10 ROP 1 EINT 2.0E5 LENM 0.5 LENP 0.5

SCOU 65 'vx_61' NSTO 61 SAXE 1.0 'curr_abscissa' LECT xaxo TERM

CSTA 0.125

AMOR QUAD 4.0 LINE 0.2

**fet402.epx**

ECHO

CAST mesh

fet402.epx

fin;

sauv form mesh;

msh = bar _tetr TERM

COMP GROU 4 'bar1' LECT bar TERM COND XB LT 0.5

'bar1' LECT bar DIFF bar TERM

'ea' LECT bar TERM COND NEAR POIN 0.25 0 0

'ab' LECT bar TERM COND NEAR POIN 0.75 0 0

maxl 3 H1 0.015 H2 0.05

maxl 3 H1 0.015 H2 0.05

maxl 3 H1 0.015 H2 0.05

MAXI GAP 10 GANN 1.5 PINI 1.40E+00 PREF 1.0E4

LECT bar TERM VERT LECT bar TERM

MATE GAZP RO 10 GAMM 1.5 PINI 1.0E6 PREF 1.0E5

ECRI COOR DEPL VITE ACCE FINT FEXT CONT ECRO TFRE 0.3E-3

WAVE 4 PLAN X 0.5 Y 0 Z 0 NX 1 NY 0 NZ 0 T0 0 C 631.54875989856 ! shock wave

MAXI 3 H1 0.015 H2 0.05

PLAN X 0.5 Y 0 Z 1 NY 0 NZ 0 C 18.200470934493 ! c.d. wave

PLAN X 0.5 Y 0 Z 1 NY 0 NZ 0 C 295.275820934493 ! c.d. wave

PLAN X 0.5 Y 0 Z 0 T0 0 C 347.298334620742 ! r. wave

> CALC TINI 0. TEND 0.60E-3

PLAY

*=================================================================

CALC TINI 0. TEND 0.60E-3

SORT VISU NSTO 61

OPTI PRIN

RESU ALIC GARD PSCR

Post-treatment (BMPs from alice file)

COLO NOIR NOIR

TRAC 3 6 AXES 1.0 'VELOC. [M/S]'

CORR 6 'vx_eb' VITE COMP 1 NOEU LECT nb TERM

CORR 5 'ro_ea' ECRO COMP 2 ELEM LECT ea TERM

CORR 4 'p_ea' ECRO COMP 1 ELEM LECT ea TERM

CORR 3 'vx_ea' VITE COMP 1 NOEU LECT na TERM

CORR 2 'ro_ea' ECRO COMP 2 ELEM LECT ea TERM

CORR 1 'p_ea' ECRO COMP 1 ELEM LECT ea TERM

PERF 'fet402t.pun'

SORT GRAP

RESU ALIC TEMP GARD PSCR

ECHO

Post-treatment (time curves from alice temps file)

LIST 65 AXES 1.0 'VELOC. [M/S]'

LIST 62 AXES 1.0 'DENS. [KG/M3]'

LIST 61 AXES 1.0 'PRESS. [PA]'

DCOU 75 'v_ana' SHTU GAMM 1.5 ROM 10 ROP 1 EINT 2.0E5 LENM 0.5 LENP 0.5

DCOU 72 'r_ana' SHTU GAMM 1.5 ROM 10 ROP 1 EINT 2.0E5 LENM 0.5 LENP 0.5

SCOU 65 'vx_61' NSTO 61 SAXE 1.0 'curr_abscissa' LECT xaxo TERM

CSTA 0.125

AMOR QUAD 4.0 LINE 0.2

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fet403.epx

fet403.epx

fet403.epx

fet403.epx
MATE GAZP RO 10 GAMM 1.5 PINI 1.E6 PREF 1.E5

WAVE 4 PLAN X 0.5 Y 0 Z 0 T0 0 C13 0.5476931418856 ! shock wave
WAVE 4 PLAN X 0.5 Y 0 Z 0 T0 0 C13 0.5476931418856 ! c.d. wave
WAVE 4 PLAN X 0.5 Y 0 Z 0 T0 0 C13 0.5476931418856 ! r. wave (right)

MAXE GASP RO 10 GAMM 3.5 FINI 1.8 PREP 1.85
LECT bar1 TERM
GASP RO 1 1 1 FINI 1 ES PREP 1.85

**

CREH FINI 1.2 PREF 1.2 TIMI 1.0000000000000000
KISS 0.0 ! Unburnt region.
ES 0.0

**

TRAX 4000.
K 0.0
NECH 0.0
MATH 1
The image contains a page of a document with mathematical and textual content. The content involves calculations and geometric transformations, particularly related to hexahedral and tetrahedral meshes. The text appears to be part of a larger technical or mathematical exposition, possibly discussing algorithms or procedures for mesh generation or manipulation.

Due to the nature of the content, the text is not easily transcribed into plain text format without losing context or accuracy. The document seems to be part of a larger technical or mathematical exposition, possibly discussing algorithms or procedures for mesh generation or manipulation.
* Pyramid # 4
  * nlow = n4; ilow = 1;
  si ( n1 < nlow ) ; nlow = n1; ilow = 2; finsi;
  si ( n6 = nlow ) ; nlow = n6; ilow = 1; finsi;
  si ( n8 = nlow ) ; nlow = n8; ilow = 2; finsi;
  si (ilow ega 1);
  t7 = manu tet4 p4 p6 p8 p9;
  t8 = manu tet4 p8 p6 p7 p9;
  sinon;
  t7 = manu tet4 p3 p4 p6 p9;
  t8 = manu tet4 p4 p6 p7 p9;
  finai;
* Pyramid # 5
  * nlow = n1; ilow = 1;
  si ( n2 < nlow ) ; nlow = n2; ilow = 2; finsi;
  si ( n3 < nlow ) ; nlow = n3; ilow = 1; finsi;
  si ( n4 = nlow ) ; nlow = n4; ilow = 1; finsi;
  si (ilow ega 1);
  t9 = manu tet4 p1 p2 p3 p9;
  t10 = manu tet4 p3 p4 p1 p9;
  sinon;
  t9 = manu tet4 p1 p2 p4 p9;
  t10 = manu tet4 p4 p3 p1 p9;
  finai;
* Pyramid # 6
  * nlow = n3; ilow = 1;
  si ( n4 < nlow ) ; nlow = n4; ilow = 2; finsi;
  si ( n8 < nlow ) ; nlow = n8; ilow = 1; finsi;
  si ( n7 < nlow ) ; nlow = n7; ilow = 2; finsi;
  si (ilow ega 1);
  t11 = manu tet4 p3 p7 p8 p9;
  t12 = manu tet4 p8 p4 p3 p9;
  sinon;
  t11 = manu tet4 p4 p3 p7 p9;
  t12 = manu tet4 p7 p8 p4 p9;
  finai;
* tetr = t1 et t2 et t3 et t4 et t5 et t6 et t7 et t8 et t9 et t10 et t11 et t12;
  * finproc tetr;

pxordpoi.proc

*$$$$ PXORDPOI

* pour ordonner une serie de points PLIN en partant de P1
* Input:
  * PLIN = objet MAILLAGE de type POI1 (ligne de points)
  * P1 = premier point de la ligne (typ POINT)
* Output:
  * PORDO = objet MAILLAGE de type POI1 (ligne de points) contenant
  * les points ordonnees a partir de P1
  * 'DEBPROC' PXORDPOI PLIN*'MAILLAGE' P1*'POINT' ;
  *------------------------------------------------------------------
  * PORDO=P1;
  * PPA=P1;
  NE='NBEL' PLIN;
  * I=0;
  'REPETER' LAB1 (NE-1);
  I=I + 1;
  * mess I;
  PLIN= 'DIFF' ((PPA 'ET' PPA) 'ELEM' 1) PLIN;
  PPA=PLIN 'POIN' 'PROC' PPA;
  PORDO=PORDO 'ET' PPA;
  'FIN' LAB1;
  * 'FINPROC' PORDO,
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Abstract

The present work completes the implementation of adaptivity routines by extending them to CEA's fluid finite elements both in 2D (TRIA and CAR1) and in 3D (TETR and CUBE). The CAR1 is treated like other 2D quadrilaterals (Q41L, FL24) as far as geometrical issues are concerned. In addition to the solid case, the activation of adaptivity for fluids requires the suitable treatment of transport terms which arise in the Eulerian or ALE forms of the governing equations. For the CEA's fluid finite elements mentioned above (TRIA, CAR1, TETR and CUBE) this is done in routines tr2me.ff (for the 2D case) and tr3me.ff (for the 3D case), respectively. Therefore, most modifications for the current implementation are concentrated in those two routines. Actually, a special version of the routines is written, valid for the mesh adaptive case.
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Stimulating innovation
Supporting legislation