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Numerical Simulation of Fast Transient Phenomena in Fluid-Structure Systems

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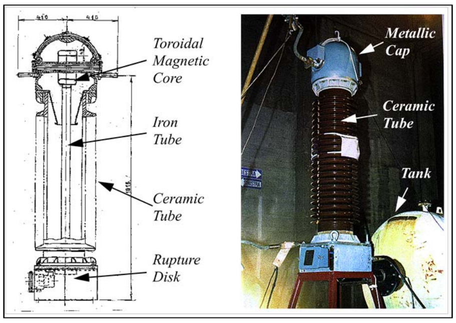
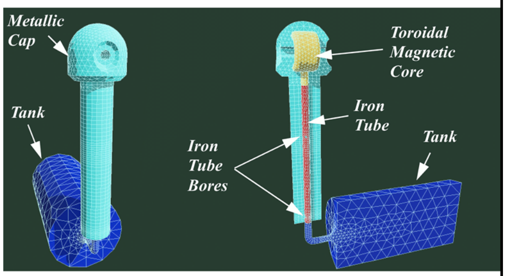
Contents

- I – Introduction (Structures)
- II – ALE formulation (Fluids)
- III – Classical Fluid-Structure Interaction
- IV – Advanced FSI (Failure/Fragmentation)
- V – Further topics and applications

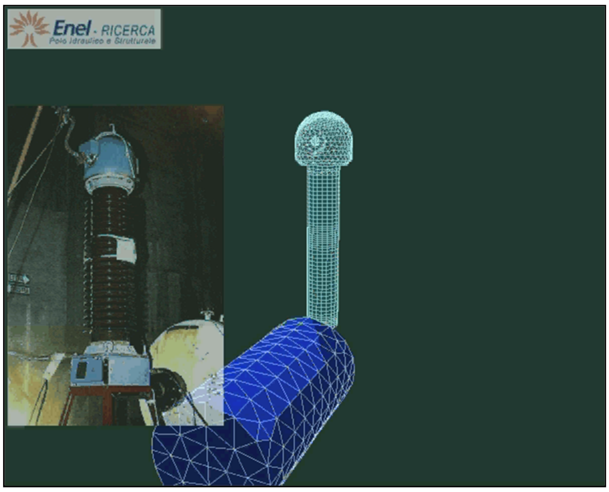
Further FSI Example

Electric arc in TA device *(Courtesy of ENEL-Hydro)*





Further FSI Example (2)



Detailed Contents (1/2)

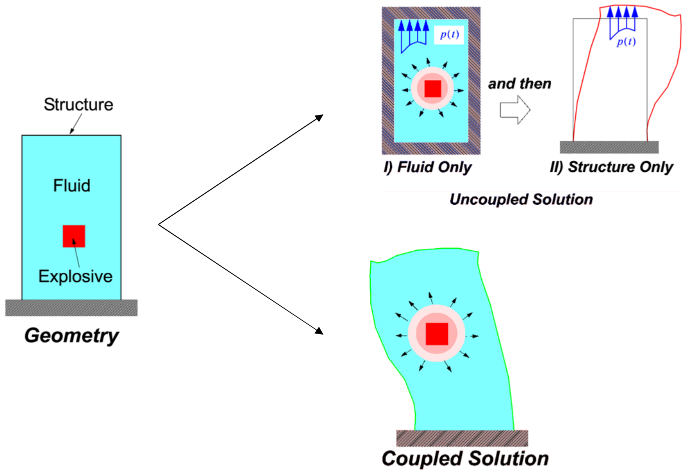
- Motivation
- A classification of FSI algorithms
- Geometrical methods:
  - The FSA/FSR method
- Equilibrium-based methods:
  - The Uniform Pressure (UP) method
- A combined method:
  - The FSCR method

Detailed Contents (2/2)

- Application to Finite Volumes:
  - Weak FSI for NCFV
  - Weak FSI for CCFV (conforming)
- Non-conforming FSI:
  - For FE / NCFV (strong approach)
  - For CCFV (weak approach)
- Some special FSI techniques/applications:
  - Modeling of perforated structures
  - Sloshing problems

FSI Motivation

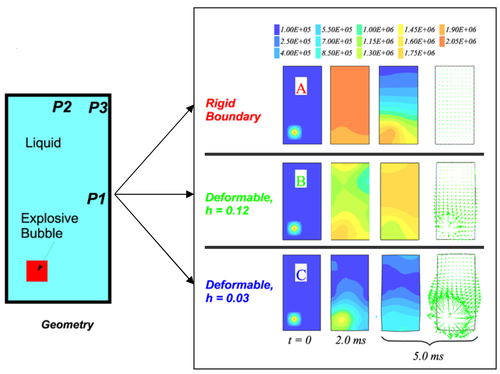
- Two possible approaches: uncoupled or fully coupled



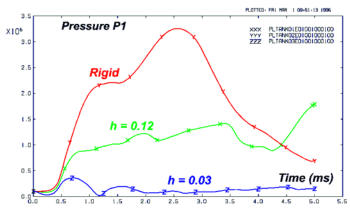
FSI Motivation (2)

Fully coupled analysis is mandatory in two classes of problems:

- With nearly incompressible fluids

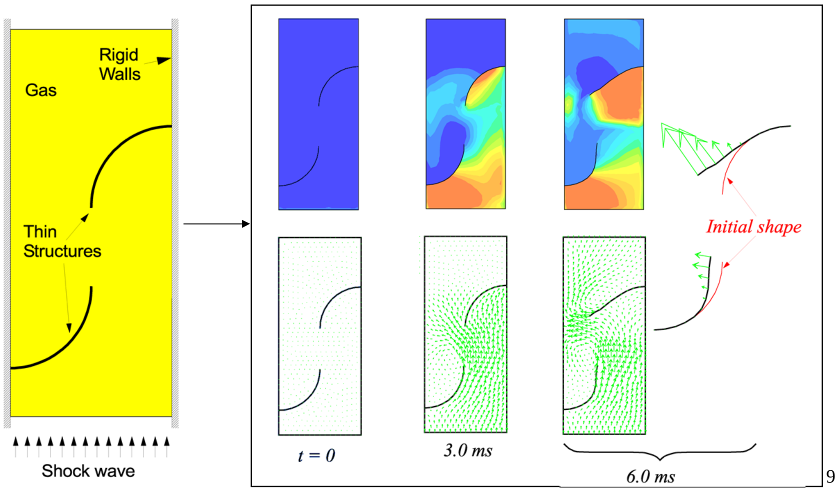


h=tank thickness



FSI Motivation (3)

- With <u>very deformable</u> structures



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A Classification of FSI Algorithms

- Each **FSI algorithm** consists of two parts:
  - A **detection** strategy
  - An **enforcement** strategy
- As concerns FSI detection, we distinguish:
  - **Basic** type (no structural failure, moderate rotations)
    - Conforming F-S meshes
    - Non-conforming F-S meshes
  - **Embedded** type (failure/fragmentation, large rotations)
- As concerns FSI enforcement, one can use:
  - **Strong** enforcement (via constraints on velocities)
  - **Weak** enforcement (via pressure forces / fluxes)

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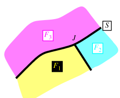
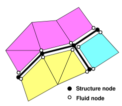
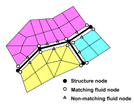
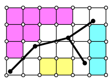
A Classification of FSI Algorithms

FSI Algorithm	**FSI Detection**	**Basic**	**No** structural **failure**, moderate rotations
		Embedded	Structure **can** fail, **arbitrary rotations**
	FSI Enforcement	**Strong**	**Constraints** on F and S **velocities** are imposed, e.g. by **Lagrange multipliers** (implicit)
		Weak	**Pressure forces** are transmitted from the fluid to the structure and **structure motion** provides weak feedback on fluid (S=master / F=slave)

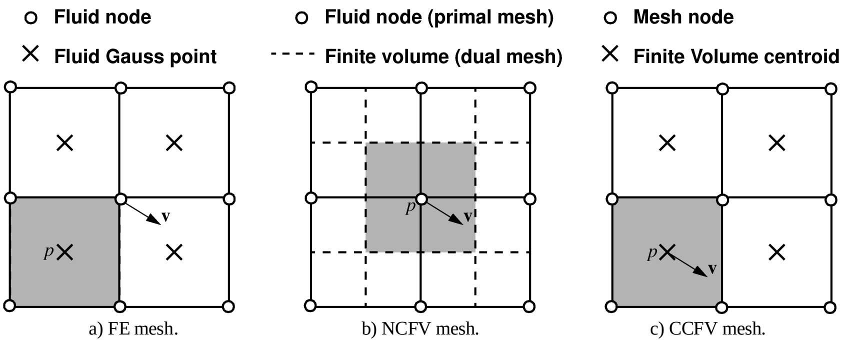
A Classification of FSI Algorithms

Available FSI Algorithms

	Detection Strategy	Spatial Discretization		Enforcement Strategy	Name / command	Use with
FSI Algorithm 	**Basic** (no structural failure)	**Conforming** F-S meshes		**Strong**	**FSA**	FE, NCFV
				Weak	Merge F-S nodes	CCFV
		Non-conforming F-S meshes		**Strong**	**FSA**	FE, NCFV
				Weak	Declare non-matching F-nodes	CCFV
	Embedded (structure can fail)	S-mesh is **Immersed** in the F-mesh		**Strong**	**FLSR**	FE, NCFV
				Weak	**FLSW**	CCFV

A Summary of FSI Algorithms

Spatial discretization for the fluid



Both components of FSI algorithms must be adjusted to the chosen type of spatial discretization

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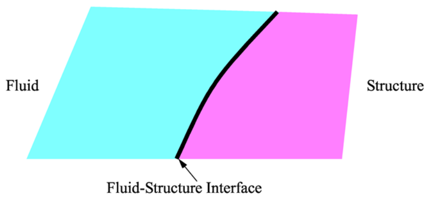
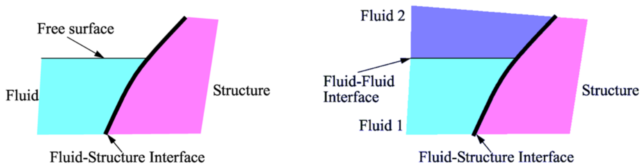
Basic FSI Algorithms

FSI for compressible, inviscid fluids can be:

- Permanent



- Non-permanent



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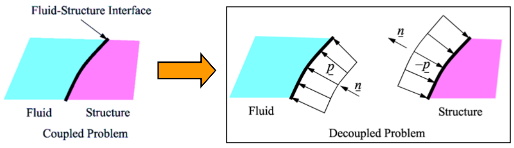
Permanent FSI treatment

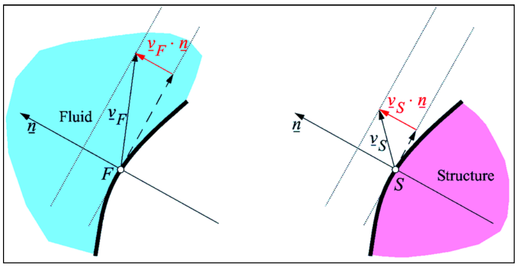
Fits naturally in ALE formulation:

- Ideally decouple problem by introducing contact pressure



- Inviscid fluid: interaction pressure acts along the normal $\underline{n}$ to the interface

- Impose material velocity compatibility condition: $\underline{v}_F \bullet \underline{n} = \underline{v}_S \bullet \underline{n}$



- Tangential velocity components are unconstrained
- Mesh velocities at interface obey: $\underline{w}_F = \underline{w}_S$

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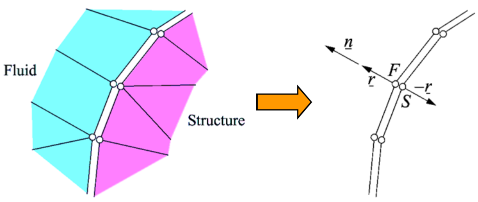
Permanent FSI treatment (2)

- Upon discretization, contact pressure is replaced by interaction force $\underline{r}$



- Interaction force $\underline{r}$ is the resultant of the contact pressure at each node of the interface

- For the moment, assume *nodal conformity* at the F-S interface
- Velocity compatibility condition $\underline{v}_F \bullet \underline{n} = \underline{v}_S \bullet \underline{n}$ is of the form $\underline{C}\underline{v} = \underline{b}$ therefore one can use Lagrange multipliers to find $\underline{r}$ (see Part 1)
- However, the following apparently simple question arises:

How does one define "the" normal to a discrete F-S interface?

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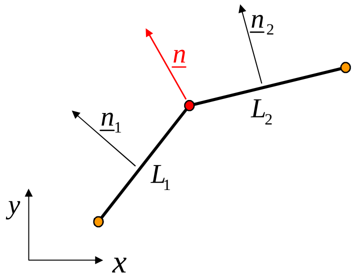
The 2-D plane case

Pioneering work (1980s) by Donea, Giuliani, Halleux:



- Physical intuition: the discrete normal is some average of the adjacent sides normals: $\underline{n} = (\underline{n}_1 + \underline{n}_2)/\|\underline{n}_1 + \underline{n}_2\|$
- Works well only in 2D plane cases, and for uniform mesh: $L_1 = L_2$
- In more general cases, the mass balance is incorrect: some fluid is “gained” or “lost” at the interface corners

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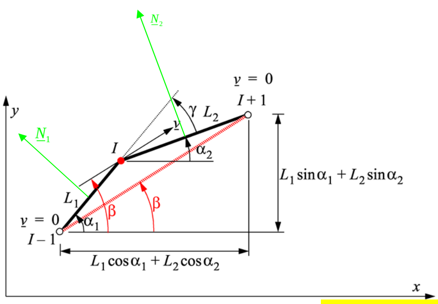
The 2-D plane case (2)

Use geometric flux of relative velocity:



- Fluid mass is conserved when: $\Phi_1 + \Phi_2 = 0$

$$\boxed{\tan\beta = \frac{L_1 \sin\alpha_1 + L_2 \sin\alpha_2}{L_1 \cos\alpha_1 + L_2 \cos\alpha_2}}$$

- Assume structure is fixed and fluid is at rest at nodes *I-1* and *I+1*, while it has velocity $\underline{v}$ of slope □ at node *I*.
- The fluid flux “entering” side L_1 is proportional to:

$$\Phi_1 = \|\underline{v} \bullet \underline{N}_1\| = vL_1 \cos(\frac{\pi}{2} + \alpha_1 - \beta) =$$
$$= vL_1 \sin(\alpha_1 - \beta)$$

- The fluid flux “entering” side L_2 is proportional to:

$$\Phi_2 = \|\underline{v} \bullet \underline{N}_2\| = vL_2 \cos(\frac{\pi}{2} + \alpha_2 - \beta) =$$
$$= vL_2 \sin(\alpha_2 - \beta)$$

- The angle □ is the slope of the line connecting nodes *I-1* and *I+1*
- When $L_1 = L_2 = L$ this reduces to: $\tan\beta = \dfrac{\sin\alpha_1 + \sin\alpha_2}{\cos\alpha_1 + \cos\alpha_2}$, i.e.: $\boxed{\beta = \dfrac{\alpha_1 + \alpha_2}{2}}$

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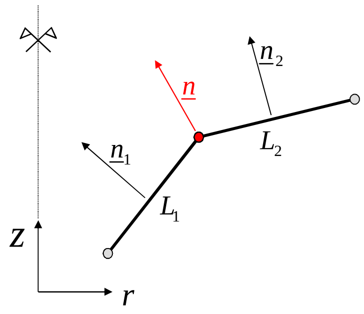
Exercise 1 – the 2-D axisymmetric case

- Find analytical expression of the normal direction in 2-D axisymmetric geometry.
- Does the geometrical property (connecting line) hold also in this case?
- Show that the obtained expression tends to the one for plane geometry as the radius tends to infinity.



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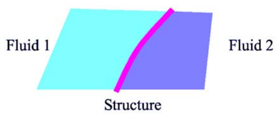
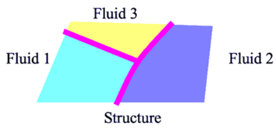
Geometrically complex cases

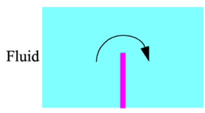
- Bilateral fluid contact:



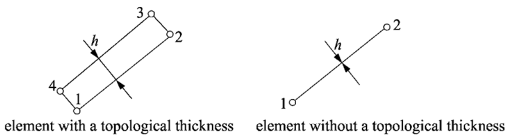
- Structural joints (bifurcations):



- Submerged structural edges:



- Structural elements without topological thickness:



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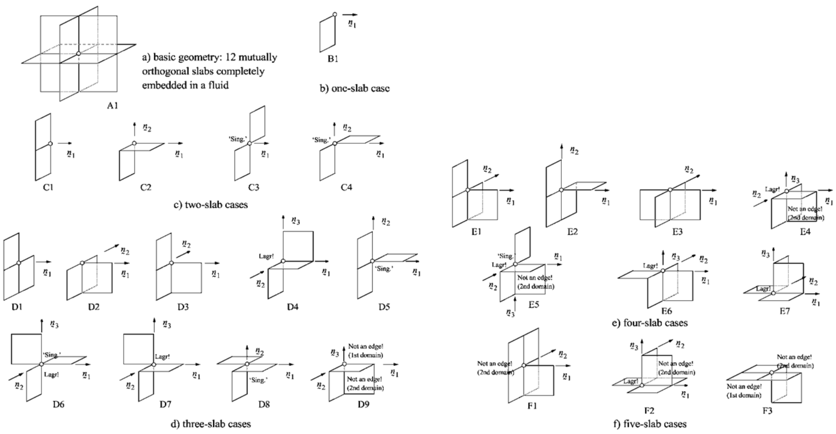
Geometrically complex cases (2)

- 3-D box-like structures:



Types of classical FSI algorithms

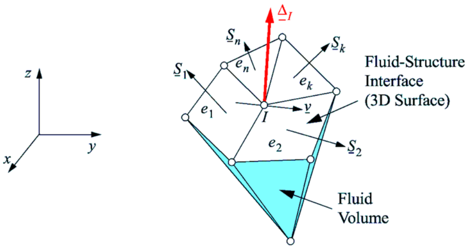
- <u>Purely geometrical</u> methods, based only upon topology of the F-S interface in the vicinity of node under consideration:
    - <u>FSA</u> algorithm (<u>F</u>luid-<u>S</u>tructure <u>A</u>LE)
- <u>Non-geometrical</u> methods, based upon equilibrium considerations:
    - <u>UP</u> algorithm (<u>U</u>niform <u>P</u>ressure)
- <u>Hybrid</u> methods:
    - <u>FSCR</u> algorithm

The FSA algorithm

- Purely geometrical method, based upon local shape of fluid domain only (avoids ambiguities due to no-thickness structural elements).
- Normal direction obtained from zero net velocity flux condition across discrete interface (no fluid gains or losses):

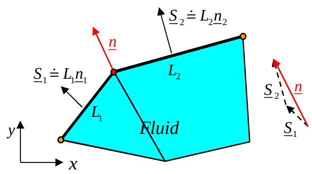
  $\underline{\Delta} \doteq$ influence domain of node

  $\underline{n} = \underline{\Delta} / \|\underline{\Delta}\|$ with $\underline{\Delta} = \sum_{k=1}^{n} \underline{S}_k$



- The 2-D plane case:

  $\boxed{\underline{n} = (\underline{S}_1 + \underline{S}_2) / \|\underline{S}_1 + \underline{S}_2\|}$



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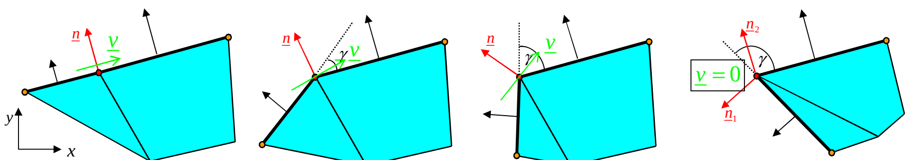
The FSA algorithm (2)

- Effect of progressive "sharpening" of interface corner:



$\gamma > \overline{\gamma} \rightarrow$ 2 normals!

- Face vectors $\underline{S}_k$ are subdivided into one or more groups. Vectors in same group form angle < than given value $\overline{\gamma}$.
- Each group is used to generate one normal.
- If the number of independent normals equals the space dimension, the node is set Lagrangian and "tied" to the structural node: $\boxed{\underline{v}_F = \underline{v}_S}$

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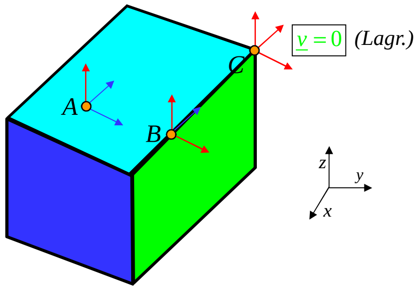
The FSA algorithm (3)

- Thus, in 3D cases one can have 1 or <u>2 normals</u> in an ALE node:



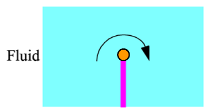
A: 1 normal (blocked), 2 free

B: 2 normals (blocked), 1 free

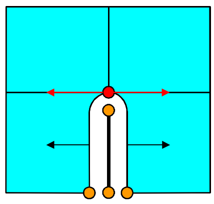
C: 3 normals (blocked), node becomes Lagrangian, tied to structure

The FSA algorithm (4)

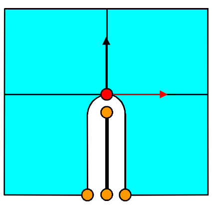
The case of submerged structural edges:



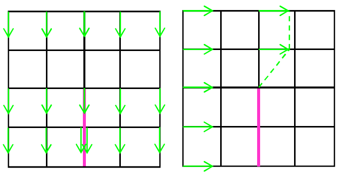
- If the structural element has <u>no topological thickness</u>, the node at the tip is a <u>singular point</u> as concerns the normal



- FSA strategy outlined so far would lead to <u>two mutually opposite normals</u>: one is <u>redundant</u> and should be rejected

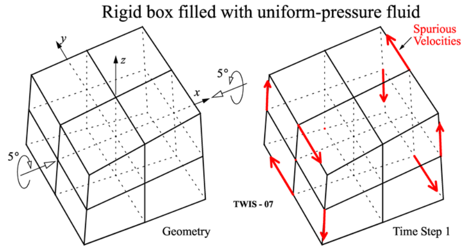


- Aligned flow is undisturbed, transversal flow “sticks” at tip



Shortcomings of the FSA algorithm

- Onset of spurious velocities in 3-D models with warped element faces. Example: patch test

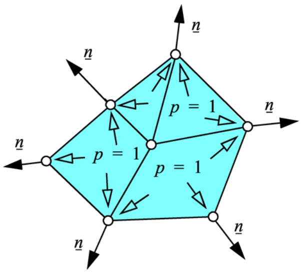


- Reason: slight but non-negligible accuracy mismatch in calculation of internal pressure forces and of reactions (direction of the normal)
- FSA method is purely geometrical and uses no information about internal fluid element formulation (e.g., spatial integration rules)

⇒ • Investigate alternative methods based on equilibrium

The UP algorithm

The method simply relies upon the observation that:



Element's pressure forces φ_p^{elem}

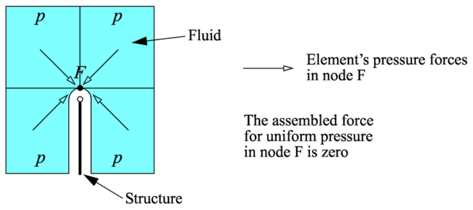
The direction of the discrete normal coincides with the resultant of internal forces due to an arbitrary but uniform pressure (say, p=1) in the whole fluid domain.

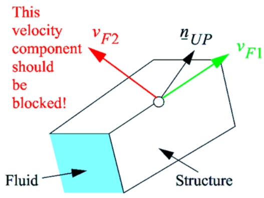
$$\underline{\varphi}_p^{\text{elem}} = \frac{1}{p}\underline{f}_p^{\text{elem}} \xrightarrow[\underline{\varphi}_p = \sum \underline{\varphi}_p^{\text{elem}}]{\text{Assembly}} \underline{n} = \underline{\varphi}_p / \left\| \underline{\varphi}_p \right\|$$

- Computationally inexpensive because $\underline{f}_p^{\text{elem}}$ are computed anyway.
- Ensures perfect equilibrium and therefore avoids shortcomings of purely geometrical methods e.g. with warped 3-D faces.

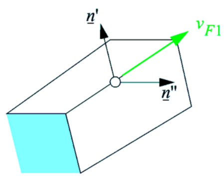
Shortcomings of the UP algorithm

- It fails at submerged structural edges with no topological thickness: the assembled force vanishes and thus the normal is undetermined.





UP Method:
One Normal

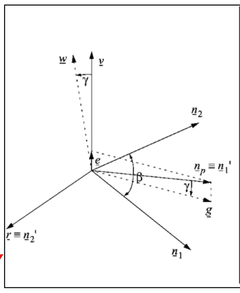


Geometric Method:
Two Normals

- It can yield at most one normal per node.

The FSCR algorithm

Combination of FSA and UP, exploiting respective strengths.



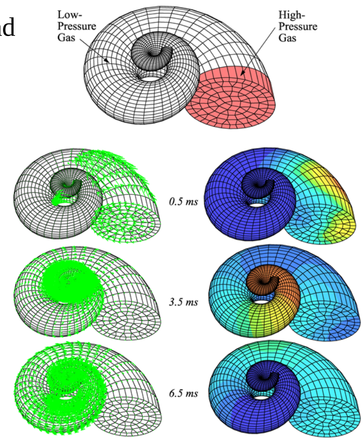
- $\underline{n}_1$, $\underline{n}_2$ and $\underline{n}_p$ are unit vectors
- In practical cases, the angle β is such that $60° \leq \beta < 180°$
- $\underline{v} = (\underline{n}_1 \times \underline{n}_2)/\|\underline{n}_1 \times \underline{n}_2\|$
  The $\underline{v}$ vector is unitary and normal to the plane defined by $\underline{n}_1$ and $\underline{n}_2$
- $\underline{e} = (\underline{n}_p \cdot \underline{v})\underline{v}$
- $\underline{g} = \underline{n}_p - \underline{e}$
- The $\underline{g}$ vector is the projection of $\underline{n}_p$ over the plane defined by $\underline{n}_1$ and $\underline{n}_2$
- $\underline{r} = (\underline{g} \times \underline{v})/\|\underline{g} \times \underline{v}\|$
- $\begin{cases} \underline{n}_1' \equiv \underline{n}_p \\ \underline{n}_2' \equiv \underline{r} \end{cases}$
- Note that $\underline{n}_1' \perp \underline{n}_2'$ by construction.

- Search normal(s) by FSA: $\underline{n}_1$ ($\underline{n}_2$).
- Search normal by UP: $\underline{n}_p$.
- If FSA yields influence domain composed only by mutually opposite faces, we know that $\underline{n}_p$ is undetermined: keep $\underline{n}_1$ ($\underline{n}_2$).

- In all other cases $\underline{n}_p$ is more accurate than $\underline{n}_1$ ($\underline{n}_2$). If there is only one FSA normal $\underline{n}_1$, we take $\underline{n}_p$ instead. Else there are two FSA normals $\underline{n}_1$, $\underline{n}_2$: we correct them so that $\underline{n}_p$ is contained in the plane defined by $\underline{n}'_1$, $\underline{n}'_2$.

The case of rigid structures (FSR)

- When structural displacements are known to be <u>negligible</u> (rigid structures), <u>only the fluid needs to be modeled</u>
- The compatibility condition simplifies to: $\underline{v}_F \bullet \underline{n} = 0$
- The normal $\underline{n}$ is <u>constant</u> in time and needs to be computed only once
- The geometric and equilibrium-based methods can be used unchanged, apart from suitable simplifications
- Practical aspect: the automatic FS directives <u>dramatically simplify</u> the prescription of boundary conditions in geometrically complex cases



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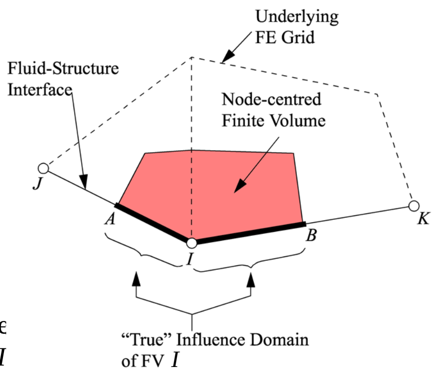
Application to NC Finite Volumes

- The FS algorithms illustrated above in a FE context have been applied with success also to node-centered FV
- Some adjustments needed as shown above, since "native" FV time integration scheme is Forward Euler (not CD)
- The two schemes can be reconciled by adding a suitable force term to the equilibrium equation
- Velocity constraint on $\underline{v}_I$ can appear "too strong" since the boundary node (I) represents the (average of the) <u>whole volume</u> I



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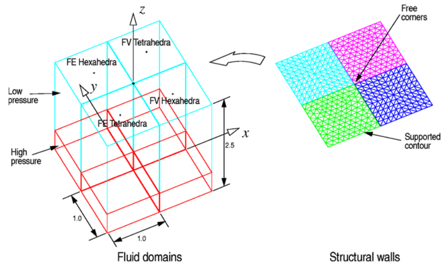
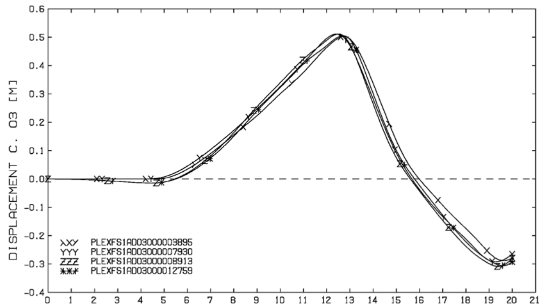
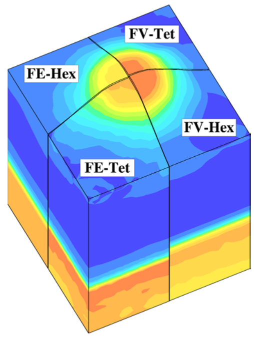
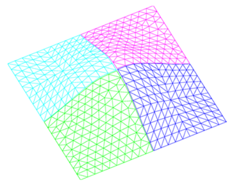
Application to NC Finite Volumes (2)

- Shock tube + FSI

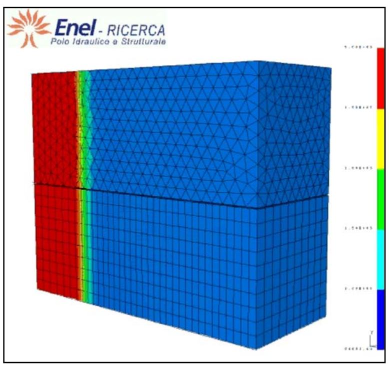


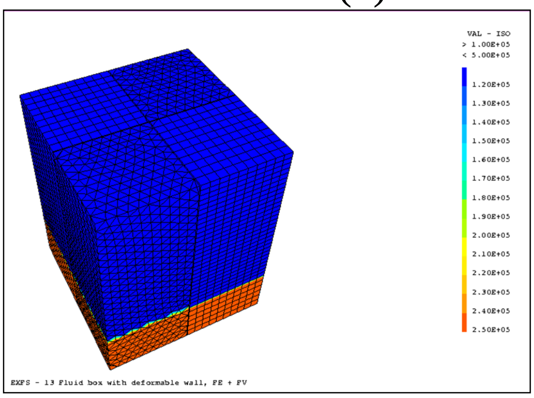


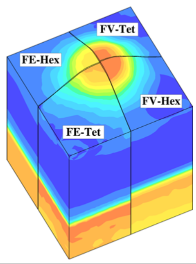




Application to NC Finite Volumes (3)







"Strong" *vs.* "Weak" Coupling

- The technique seen so far for the enforcement of boundary conditions, in particular of FSI, is sometimes denoted as **strong** coupling
- In fact, F and S are "strongly" linked together by the imposed constraints on velocities at F-S interface
- Especially in the CFD community, there exists another technique, sometimes called **weak** coupling
- In this technique, suitable fluid pressure forces are introduced and transmitted to the structure
- The structure (alone) then determines the motion of the F-S interface, and this provides a ("weak") feedback on the physical status of the fluid (via interface velocity)

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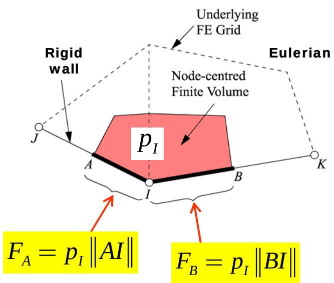
Weak BCs in NCFV

- "Weak" treatment of boundary conditions can be chosen in the NCFV model by adding the optional keyword `WBC`

`OPTI MC … WBC`

- In this case, the **LINK** directive should of course be omitted
- At the moment, this is limited to the representation of rigid walls in Eulerian calculations (no structure!)
- The code automatically recognizes the boundaries and applies suitable "external" pressure forces to the fluid



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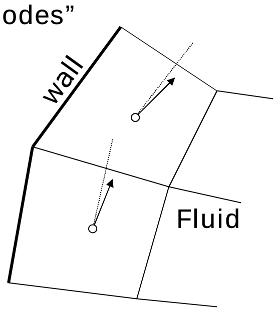
Boundary Conditions in CC Finite Volumes

("Weak" formulation only, at the moment)

- Note : fluid velocities (like all other quantities) are defined at the volume centres, not at "nodes"
- At volume faces on the fluid boundary, fluxes are **not** computed (no neighbor)
- Therefore, zero normal velocity condition is "automatically" satisfied (in an approximate way) at a rigid wall (and, in a weak manner, also at cell centres)



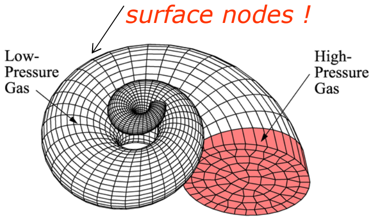
- If a structure is attached (merged nodes) to the fluid boundary, the code automatically computes pressure forces and applies them to the structure (weak FSI coupling) : no need to specify any link condition

FSI with C-C Finite Volumes

(for a conforming FS mesh)

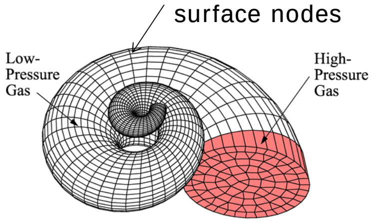
- To represent a rigid structural boundary, just leave the boundary "nodes" free (no need to use FSR condition)
- No flux calculation takes place at the boundary since volumes on the interface have no neighbors : a rigid-wall condition results automatically

No condition on surface nodes !



C-C FV

FSR condition on surface nodes



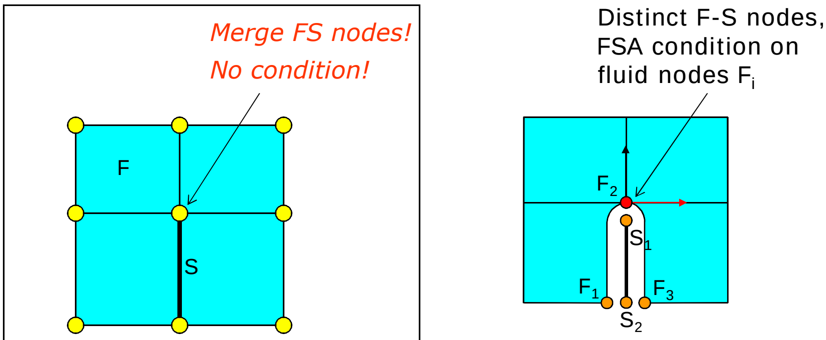
FE or N-C FV

(Strong coupling)

FSI with C-C Finite Volumes (2)

(for a conforming FS mesh)

- To represent a <u>deformable structural boundary</u>, just <u>merge</u> the structure and fluid nodes (no need to use FSA condition)



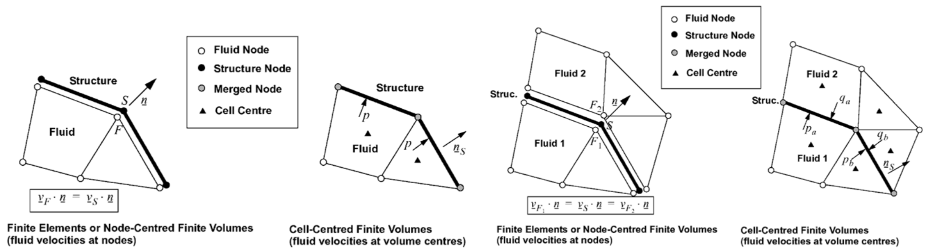
C-C FV　　　FE or N-C FV

FSI with C-C Finite Volumes (3)

(for a conforming FS mesh)

- The same technique works also in case of “double” (two-sided) FS Interface

Single FS Interface　　　Double FS Interface

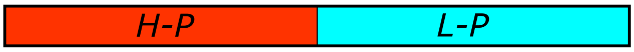


FE or N-C FV　　C-C FV　　FE or N-C FV　　C-C FV

- The fact that velocities are discretized at cell centres facilitates the treatment of <u>structure fragmentation</u> (see Part IV)

Exercise 1a – Shock Tube

(FE / FV, Strong / Weak BCs)



- Obtain various solutions and compare them with analytical solution (single-component perfect gas):
  - FE, strong BCs
  - NCFV, strong BCs
  - NCFV, weak BCs
  - CCFV, weak BCs

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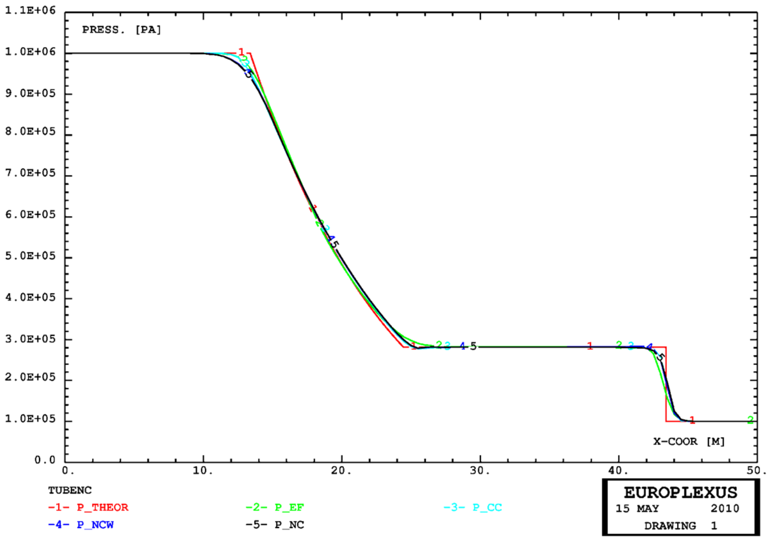
Exercise 1a – Shock Tube

- Fluid pressures (red curve is the analytical solution)



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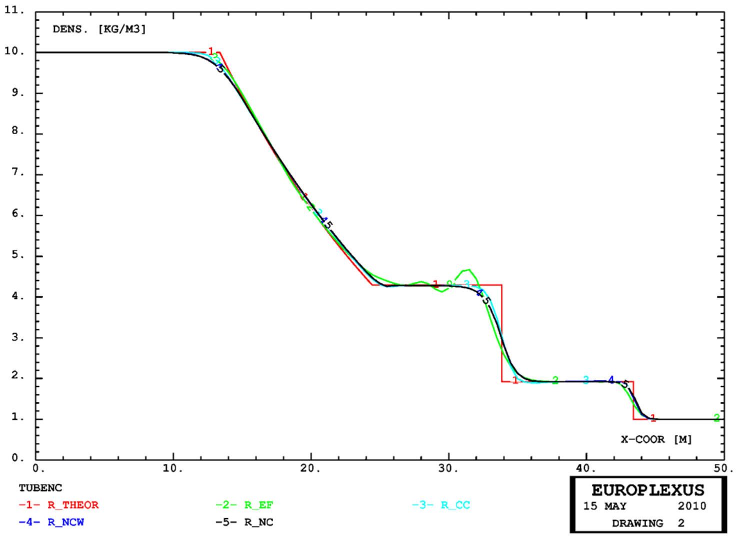
Exercise 1a – Shock Tube

- Fluid densities (red curve is the analytical solution)



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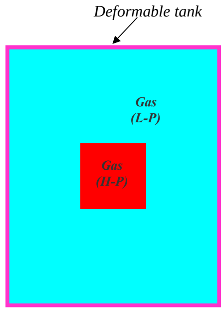
Exercise 2 – Explosions in simple deformable containers

Add a deformable structure to the case studied in exercise 2 of Part II (air-filled tank).

- Try out ALE solution with FSA



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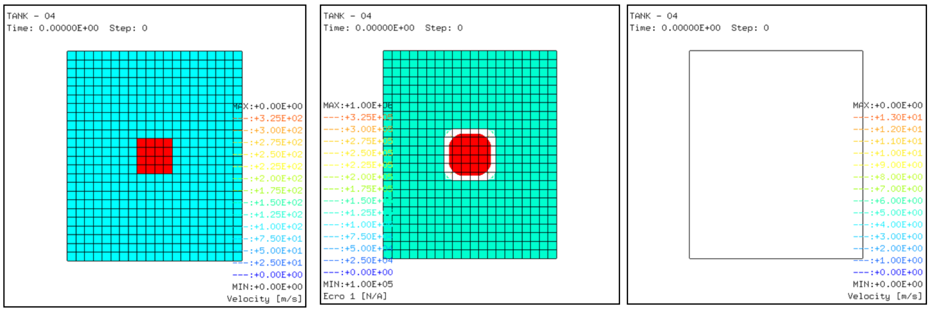
Exercise 2 – Explosions in simple deformable containers (2)

- ALE solution with FSA (TANK04):

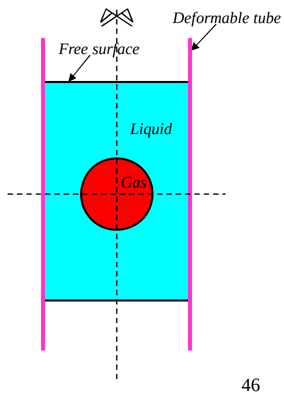


Velocities *Fluid Pressures* *Structure Velocities*

Exercise 2 – Explosions in simple deformable containers (3)

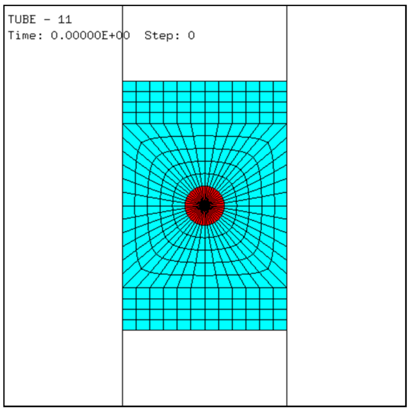
Treat as deformable the tube of the case studied in exercise 3 of Part II.

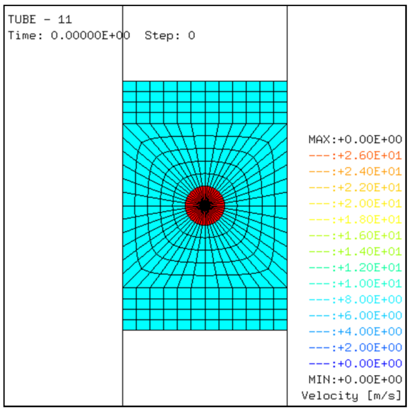
- Can one try out ALE solution with FSA?
- Alternative 1: use Lagrangian sliding
- Alternative 2: use FSA with multi-phase multi-component fluid model



Exercise 2 – Explosions in simple deformable containers (4)

- Alternative 1: use <u>Lagrangian sliding</u> (TUBE11):

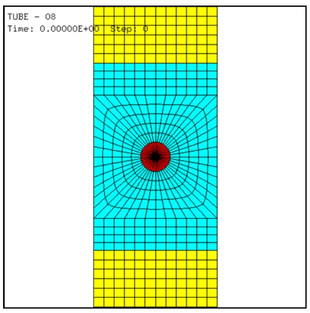


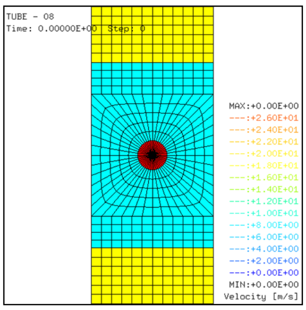


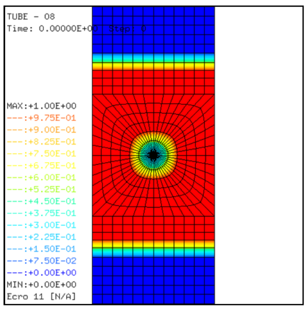
Mesh *Velocities*

Exercise 2 – Explosions in simple deformable containers (5)

- Alternative 2: use <u>multi-phase multi-component fluid model</u> (TUBE08):





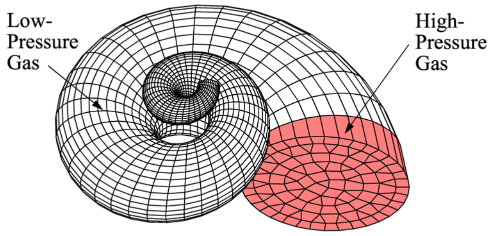


Mesh *Velocities* *Liquid fraction*

Exercise/Example 3 – Wave propagation in 3-D rigid tank

The rigid outer surface has a complex 3-D shape.

- Try out ALE solution with FSR



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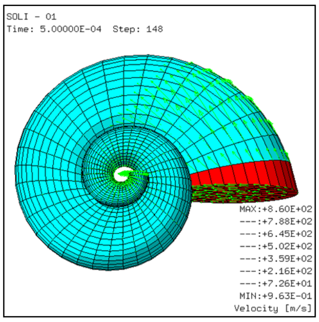
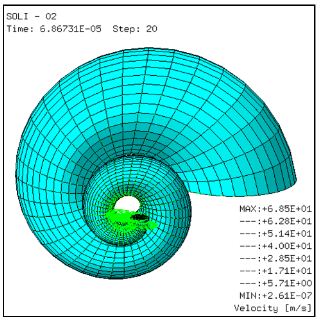
Exercise/Example 3 – Wave propagation in 3-D rigid tank (2)

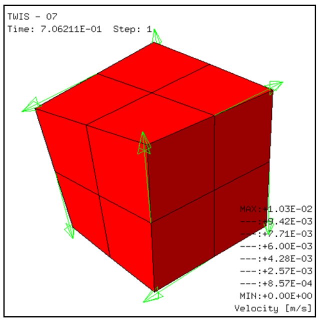
Spurious velocities:



FSR



FSR (Uniform pressure case)

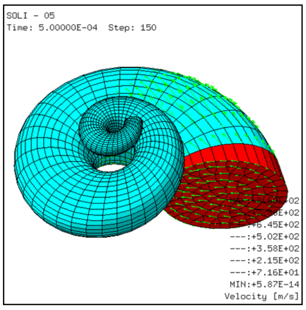


FSR (Patch test)

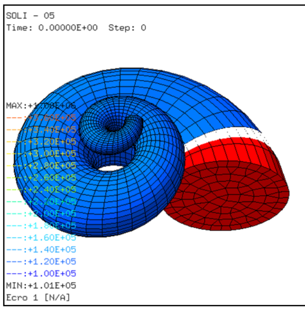
50

Exercise/Example 3 – Wave propagation in 3-D rigid tank (3)

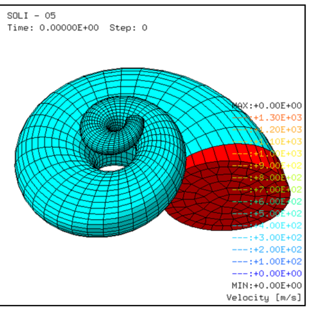
Solution with FSCR (SOLI05):



Velocities at 0.5 ms



Pressure



Velocity

Exercise/Example 3 – Wave propagation in 3-D rigid tank (4)

- *EUROPLEXUS input file (SOLI05):*

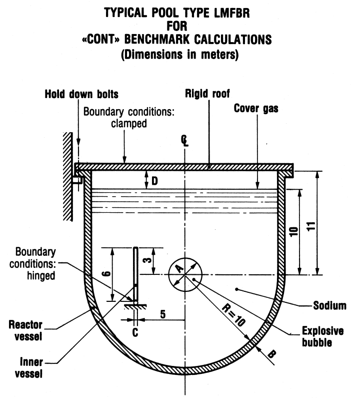
```
SOLI - 05
*-----------------------------------------------------------------
 ECHO
 CONV win
CAST MESH
*---------------------------------------------------------Problem type
TRID EULE
*---------------------------------------------------------Dimensioning
DIME
 PT3L 8760 FL38 6264 FL36 2016 ZONE 2
 NALE 1 NBLE 1
TERM
*-------------------------------------------------------------Geometry
GEOM FL38 SUR8 FL36 SUR6 TERM
*------------------------------------------------Geometric Complements
COMP COUL roug LECT sur1 TERM
          turq LECT sur2 TERM
*--------------------------------------------------------Material data
MATE FLUT RO 1.22 EINT 3.046E6 GAMM 1.269 PB 0
          ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
          CQ 2.56 PMIN 0 NUM 1
          LECT SUR1 TERM
     FLUT RO 0.1237 EINT 3.046E6 GAMM 1.269 PB 0
          ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
          CQ 2.56 PMIN 0 NUM 1
          LECT SUR2 TERM
*--------------------------------------------------Boundary conditions
OPTI FSCR
LINK COUP FSR LECT FSRN TERM
*--------------------------------------------------------------Outputs
ECRI VITE ECRO TFRE 7.0E-5
     ELEM LECT 1 TERM
     POIN LECT 1 TERM
     FICH K2000 TFRE 0.5E-3 POIN TOUS
                VARI DEPL VITE ECRO ECRC LECT 1 TERM
     FICH ALIC TFRE 7.0E-5
*--------------------------------------------------------------Options
OPTI NOTE
     CSTA 0.5
     LOG 1
*-------------------------------------------------Transient calculation
CALCUL TINI 0 TEND 7.0E-3
```

```
*===============================================================ANIMATION
PLAY

CAME   1 EYE   2.95448E-01 -5.06866E+00  6.53167E+00
!        Q     9.56305E-01  2.92372E-01  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  5.59193E-01 -8.29038E-01
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  8.29038E-01  5.59193E-01
         FOV   1.68819E+01

scen
     vect scav
     text vsca
     lima on
     colo pape

sler cam1 1 nfra 1

freq 0 tfre 0.5e-3

go
trac offs fich bmp rend

freq 0 tfre 7.0e-3
go

ENDPLAY
*=======================================================================
FIN
```

Exercise/Example 4 – CONT problem

Three fluids plus deformable structures

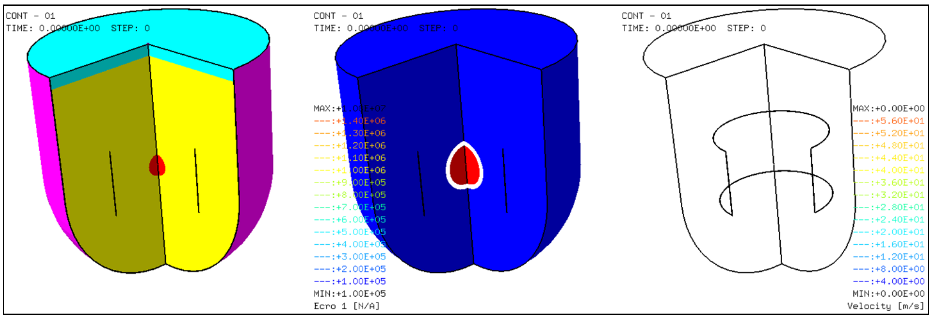
- Try out ALE solution with Lagrangian fluid/fluid interfaces (single-component fluid model)
- Try out ALE solution with ALE fluid/fluid interfaces (multi-phase multi-component fluid model)



A	1.989	m
B	0.025	m
C	0.025	m
D	1.000	m
Temp.	723	K

Exercise/Example 4 – CONT problem (2a)

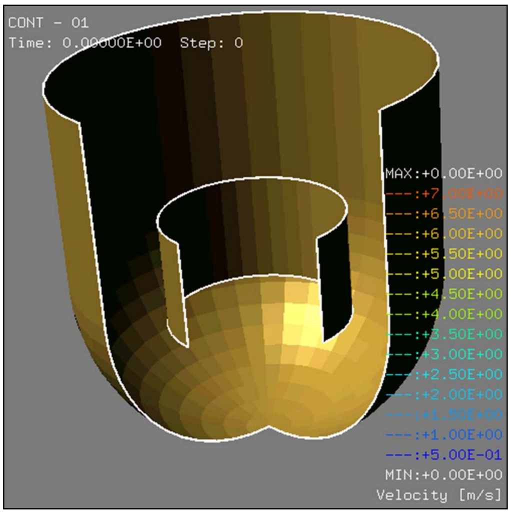
- ALE solution with Lagrangian fluid/fluid interfaces (<u>single-component</u> fluid model) (CONT01):



Materials *Pressures* *Velocities*

Exercise/Example 4 – CONT problem (2b)

- ALE solution with Lagrangian fluid/fluid interfaces (<u>single-component</u> fluid model) (CONT01):



Structure Motion and Velocities

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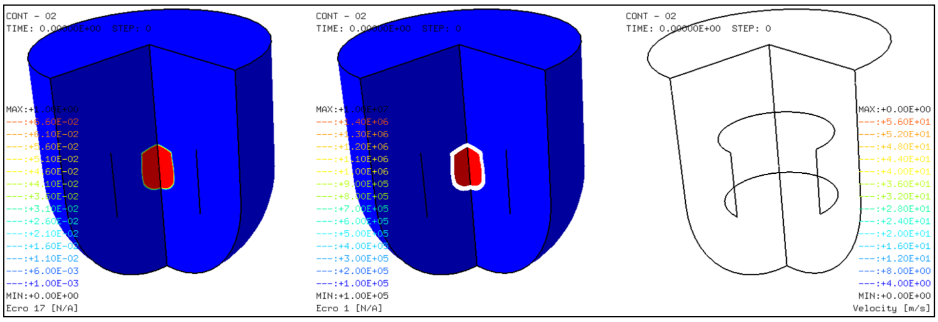
Exercise/Example 4 – CONT problem (3a)

- ALE solution with ALE fluid/fluid interfaces (<u>multi-phase multi-component</u> fluid model) (CONT02):

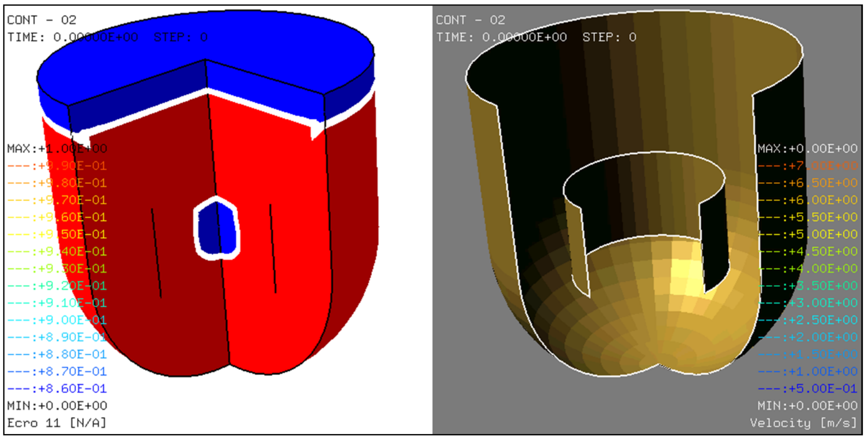


Bubble fraction *Pressure* *Velocity*

56

Exercise/Example 4 – CONT problem (3b)

- ALE solution with ALE fluid/fluid interfaces (<u>multi-phase multi-component</u> fluid model) (CONT02):



Sodium fraction *Structure Motion and Velocities*

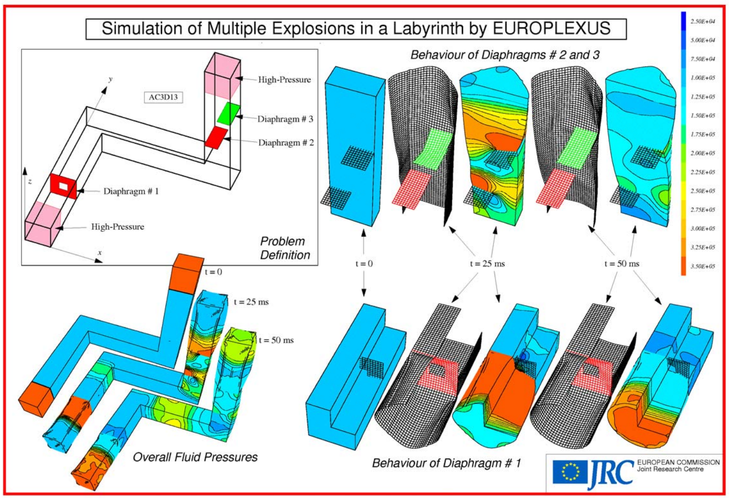
Exercise/Example 4 – CONT problem (4)

- *EUROPLEXUS input file (CONT02):*

```
CONT - 02
*-----------------------------------------------------------------------
 ECHO
CAST mesh
!CONV win
*------------------------------------------------------------Problem type
AXIS ALE
*------------------------------------------------------------Dimensioning
DIME
   PT2L 278 PT3L 35 ZONE 3
   ED01 33 FL24 230 FL23 28
   NALE 18 NBLE 278
   ECRO 13128
TERM
*----------------------------------------------------------------Geometry
GEOM ED01 stru FL23 flui3 FL24 flui4 TERM
*----------------------------------------------------Geometric Complements
COMP EPAI 2.5E-2 LECT stru TERM
*-------------------------------------------------------------Grid motion
GRIL LAGR LECT stru TERM
     AUTO AUTR
*-----------------------------------------------------------Material data
MATE VM23 RO 7800. YOUN 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT vessel TERM
     VM23 RO 7800. YOUN 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT shield TERM
     FLMP NLIQ 1 NGAS 2
     FLUT RO 832. EINT 98.68 GAMM 7.15D0 CL 0.5 CQ 2.56
          PB 2.71E5 PMIN 0. AHGF 0. ITER 2 ALF0 1.
          BET0 1. KINT 0 NUM 5
          LECT liqu TERM
     FLUT RO 2.4278E3 EINT 0. GAMM 0.75D0 CL 0.5 CQ 2.56
          PB 0. PMIN 0. AHGF 0. ITER 2 ALF0 1.
          BET0 1. KINT 0 NUM 4
          LECT bull TERM
     FLUT RO .242777373 EINT 6.865E5 GAMM 1.6 CL 0.5 CQ 2.56
          PB 0. PMIN 0. AHGF 0. ITER 2 ALF0 1.
          BET0 1. KINT 0 NUM 1
          LECT gas TERM
```

```
*-----------------------------------------------------Boundary conditions
LINK COUP
     BLOQ 1 LECT p2p TERM
     BLOQ 123 LECT p4p TERM
     CONT SPLA NX 1 NY 0 LECT symax TERM
     CONT SPLA NX 0 NY 1 LECT top   TERM
     FSA  LECT fsan TERM
*-----------------------------------------------------------------Outputs
ECRI COOR DEPL VITE ACCE CONT ECRO TFRE 250.E-3
     FICH ALIC TEMP FREQ 1
               POIN LECT p0 TERM
     FICH ALIC TFRE 2.5E-3
*-----------------------------------------------------------------Options
OPTI NOTE
     log 1 csta 0.5
     REZO GAM0 0.8
     FLMP EPS1 1.E-5
*---------------------------------------------------Transient calculation
CALCUL TINI 0.0 TEND 250.E-3
*========================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1000.0 'Time [ms]'
*-----------------------------------------------------Curve definitions
COUR 1  'dy_1'    DEPL COMP 2 NOEU LECT p0  TERM
*-------------------------------------------------------------------Plots
trac 1 axes 1.0 'DISPL. [M]' yzer
*--------------------------------------------------Results qualification
QUAL DEPL COMP 2 LECT  p0 TERM REFE -1.23718E-1 TOLE 1.E-2
*======================================================================
FIN
```

Exercise/Example 5 – Explosion in a 3-D Labyrinth



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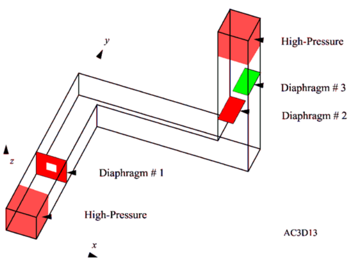
Exercise/Example 5 – Explosion in a 3-D Labyrinth

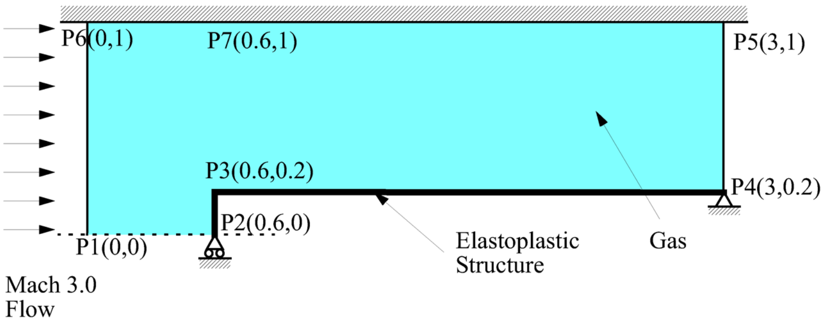


EUROPLEXUS
AC3D13
(Explosions in a 3D
Labyrinth)

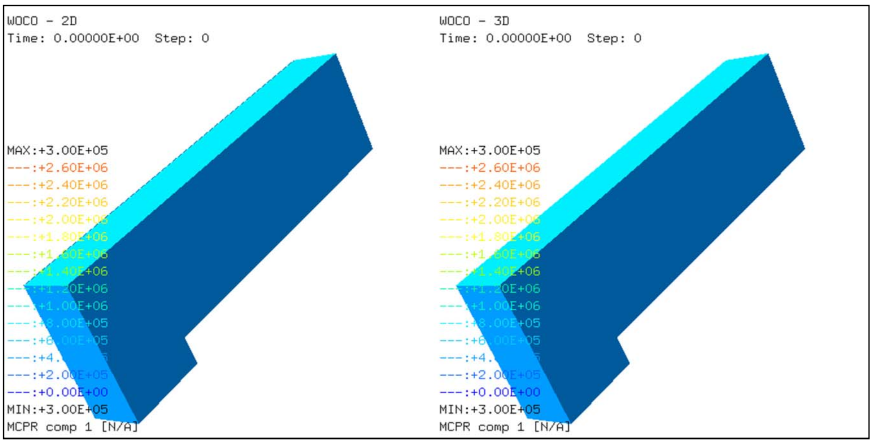
60

Exercise/Example 6 : Woodward-Colella Test (Node-Centered FV with deformable step)

Set up NC-FV model and treat the step as deformable:



Exercise/Example 6 : Woodward-Colella Test (2)

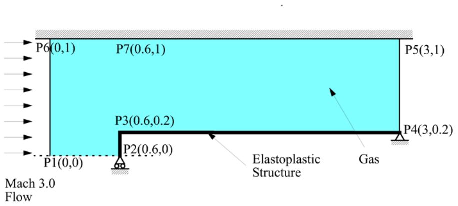


2D Solution (Pressure) *3D Solution (Pressure)*

Exercise/Example 6 : Woodward-Colella Test (3)

Mesh generation (2D):

```
*%siz 100
*
opti echo 1 dime 2 elem qua4;
opti titr 'WOCO - 2D';
*
p1 = 0 0;
p2 = 0.6 0;
p3 = 0.6 0.2;
p4 = 3 0.2;
p5 = 3 1;
p6 = 0 1;
p7 = 0.6 1;
tol = 0.001;
*
in = p1 d 40 p6;
s1 = in tran 24 (0.6 0);
s1 = chan s1 tri3;
*
la = p3 d 32 p7;
s2 = la tran 96 (2.4 0);
s2 = chan s2 tri3;
*
lh1 = p1 d 24 p2;
lh2 = p3 d 96 p4;
lh3 = p5 d 120 p6;
lv  = p2 d 8 p3;
out = p4 d 32 p5;
*
lfsa = lh2 et lv;
*
flui = s1 et s2;
mesh = flui et lfsa et in et out et lh1 et lh3;
```




```
elim tol mesh;
*
p2s = p2 'PLUS' p1;
p3s = p3 'PLUS' p1;
p4s = p4 'PLUS' p1;
strt = p2s d 8 p3s d 96 p4s;
*
mesh = mesh et strt;
*
tass mesh;
*
opti sauv form 'woco2d.msh';
sauv form mesh;
opti trac psc ftra 'woco2d_mesh.ps';
trac mesh;
trac qual mesh;
```

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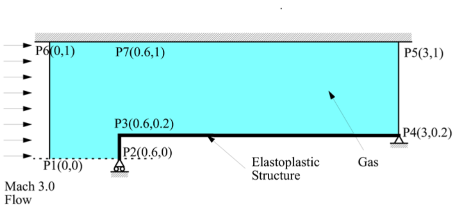
Exercise/Example 6 : Woodward-Colella Test (3)

Input (2D):

```
WOCO - 2D
ECHO
!CONV win
CAST MESH
DPLA ALE
DIME PT2L . . . TERM
GEOM
  MC23 flui
  ED01 strt
  CL22 in out
TERM
EPAI 0.020 LECT strt TERM
GRIL LAGR LECT strt   TERM
     EULE LECT in out TERM
     AUTO AUTR
$ multicomponent material
MATE MCGP NCOM 2 R 8312.
          COMP 'Air' PM 28.96 CV1 20780 CV2 0 CV3 0
          COMP 'Nitrogen' PM 28.96 CV1 20780 CV2 0 CV3 0
          LECT flui TERM
     MCFF BDFO 3 TEMP 400. PRES 300000.
          VEL1 1202.7 VEL2 0. VEL3 0.
          COMP 'Air'       MFRA 1.
          COMP 'Nitrogen'  MFRA 0.
          LECT in out TERM
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT strt TERM
```




```
INIT MCOM COMP 'Air'      MFRA 1.0 LECT TOUS
          COMP 'Nitrogen' MFRA 0.0 LECT TOUS
          PRES 300000.     LECT TOUS
          TEMP 400.        LECT TOUS
          VEL1 1202.7      LECT TOUS
          VEL2 0.00        LECT TOUS
          VEL3 0.00        LECT TOUS
LINK COUP
     BLOQ 123 LECT p4s          TERM
     BLOQ 2   LECT p2s lh3 lh1  TERM
     FSA      LECT lfsa         TERM
$
ECRI . . .
$
OPTI NOTE CSTA 0.5
OPTI MC ORDR 2 NUFL ROE rezo gam0 0.5 log 1
CALCUL TINI 0 TEND 3.5E-3
```

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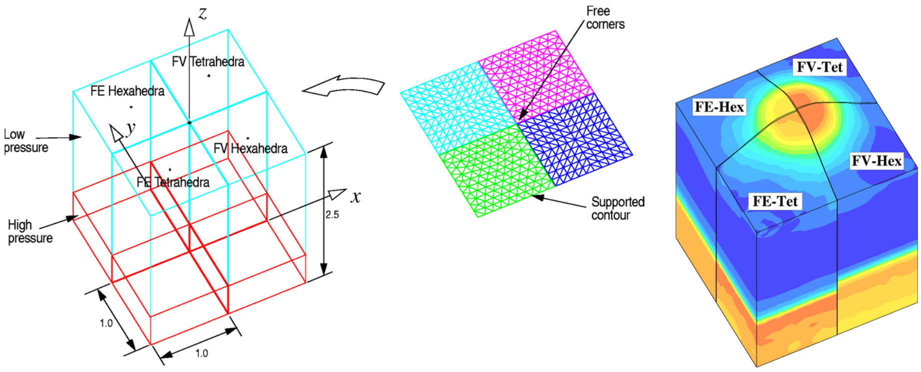
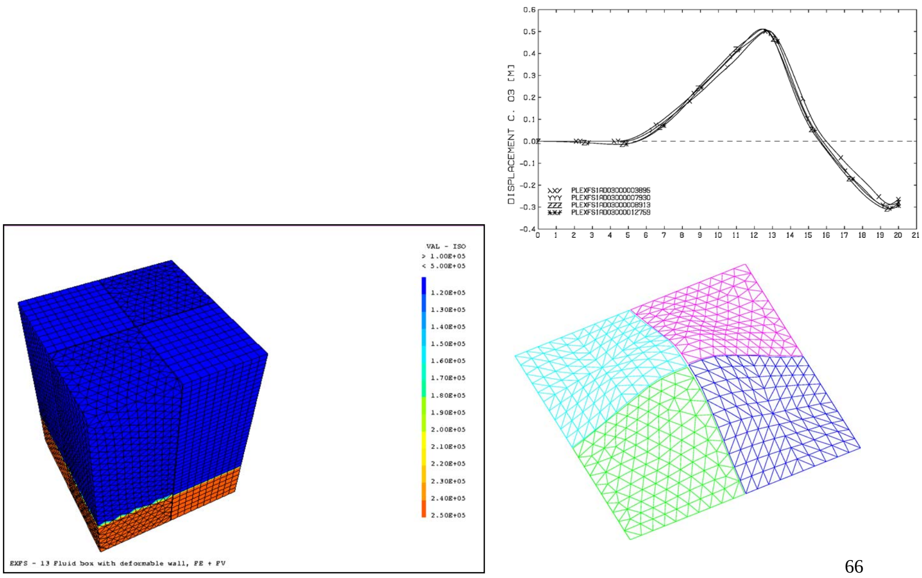
Exercise/Example 7 : Exfs Test (Comparison FE / NC-FV)

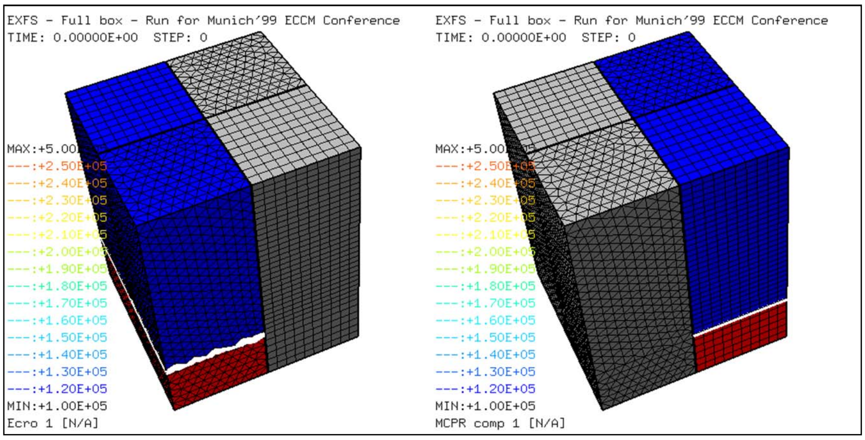


Fluid domains Structural walls

Exercise/Example 7 : Exfs Test (2)



Exercise/Example 7 : Exfs Test (3)



FE *FV*

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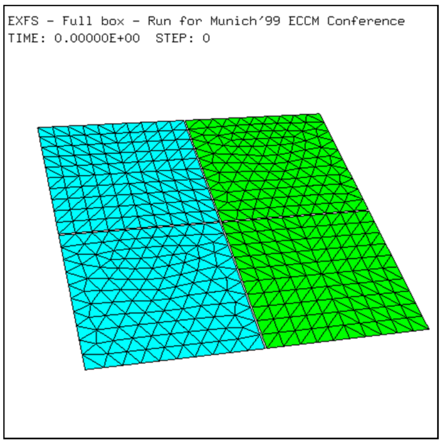
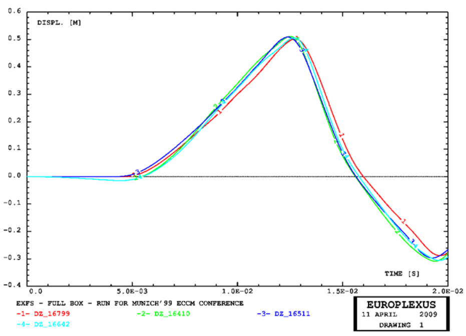
Exercise/Example 7 : Exfs Test (4)





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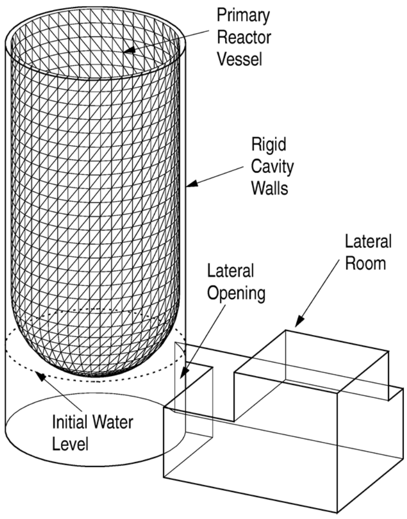
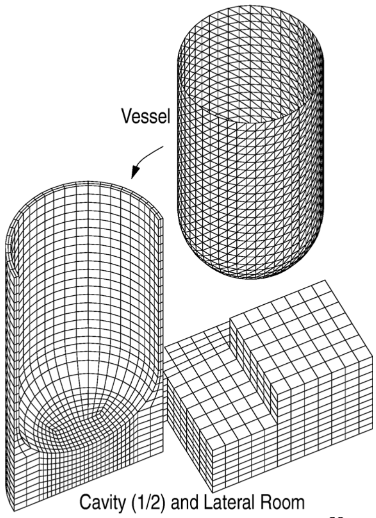
Exercise/Example 8
Steam Explosion in Reactor Cavity

Geometry:





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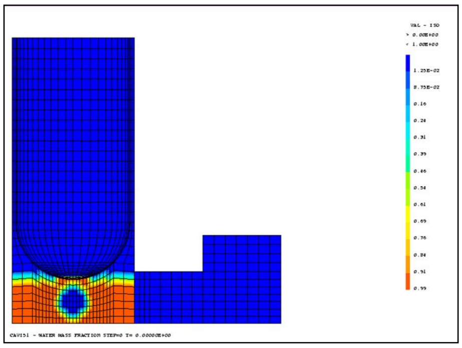
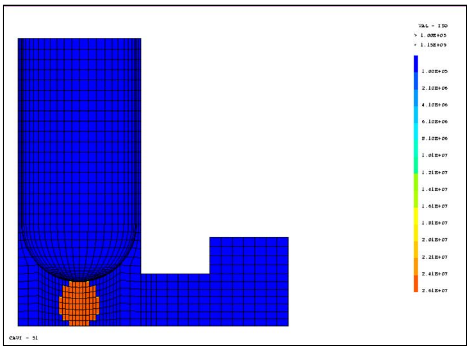
Exercise/Example 8 : Steam Explosion in Reactor Cavity (2)



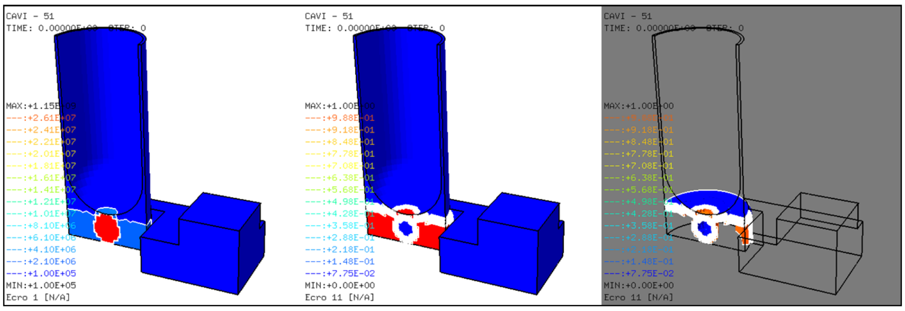


Water mass fraction

Pressure

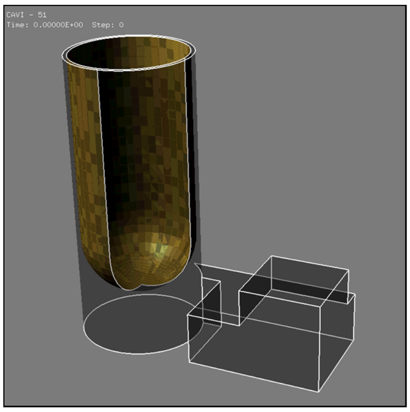
70

Exercise/Example 8 : Steam Explosion in Reactor Cavity (3)

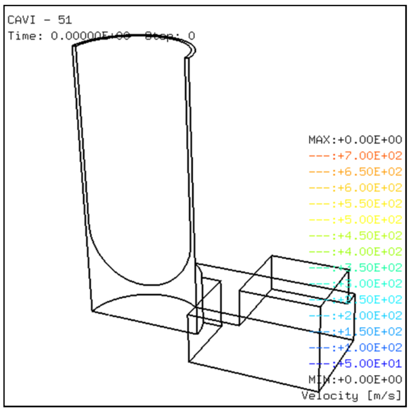


Pressure *Water* *Water (surfaces)*

Exercise/Example 8 : Steam Explosion in Reactor Cavity (4)



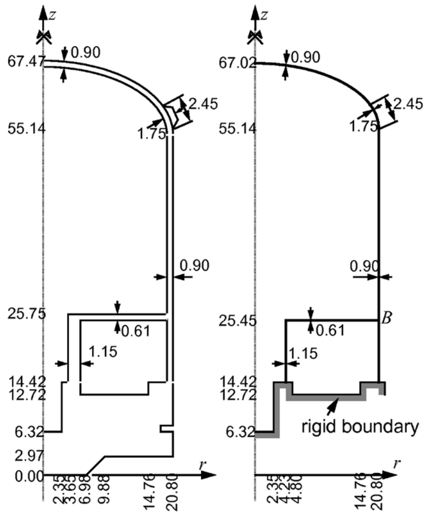
Structure



Velocities

Exercise/Example 9
Explosion in Secondary Containment

Geometry:



Layer N.	φ_L	Material
1	0.1	concrete
2	0.01	steel
3	0.78	concrete
4	0.01	steel
5	0.1	concrete

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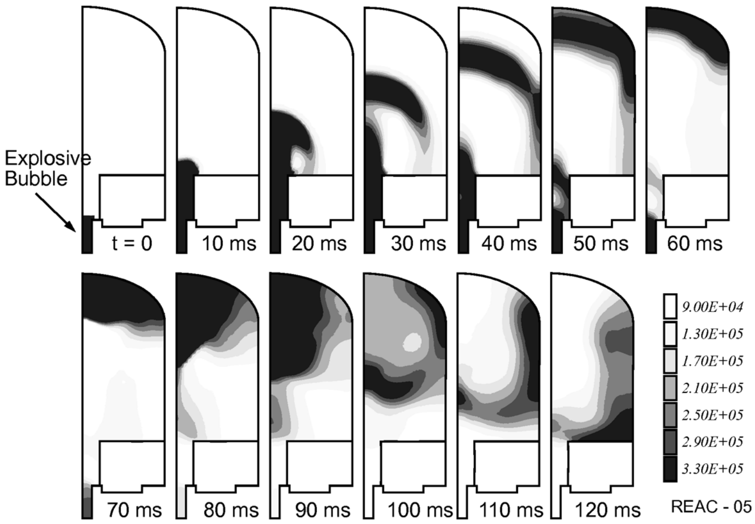
Exercise/Example 9
Explosion in Secondary Containment (2)

Geometry:



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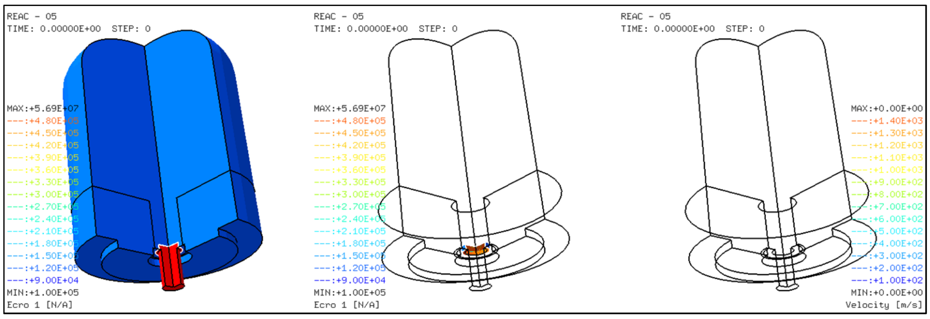
REAC - 05

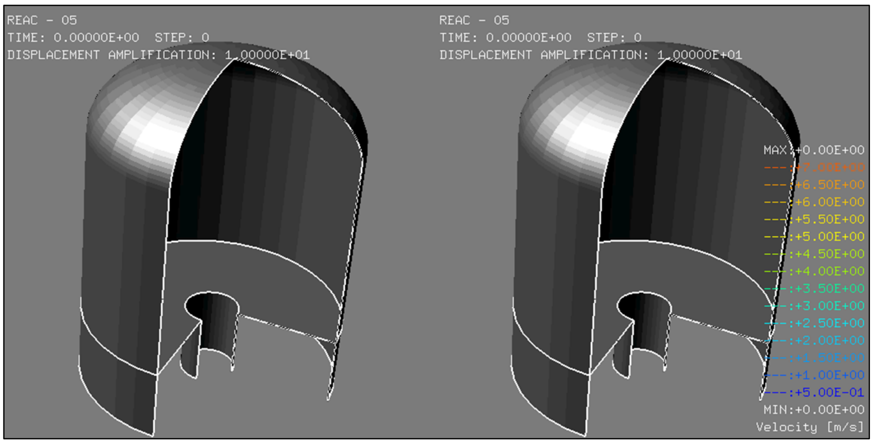
Exercise/Example 9
Explosion in Secondary Containment (3)



Pressure *Pressure (surfaces)* *Velocities*

75

Exercise/Example 9
Explosion in Secondary Containment (4)



Structure *Structure velocities*

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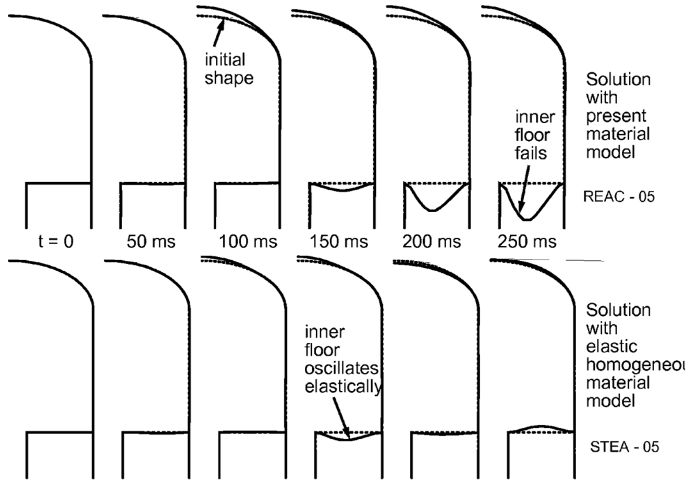
Exercise/Example 9
Explosion in Secondary Containment (5)

Comparison of elastic and reinforced concrete (elastoplastic) material solutions:



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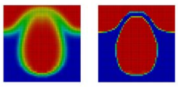


Power excursion in a reactor with anti-diffusion (Courtesy of CEA)

Accident scenario: power excursion in a nuclear reactor core

↓

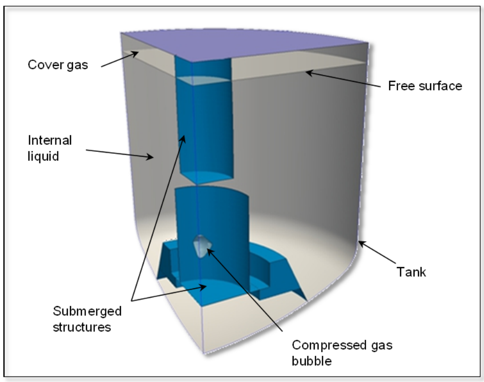
Generation of a high-pressure bubble (heat exchange fluid vapor and other components)

↓

Pressure waves on the tank: necessary to **dimension the confinement** to avoid leakage

Very complex physics in the core region (*FCI*)

Classically dimensioning realised by means of **simplified tests** with well-known components:
- **Explosive** instead of fuel / coolant interaction
- **Water** instead of the real coalant
- **No phase changes**



MARA10 test case for the dimensioning of a SFR tank

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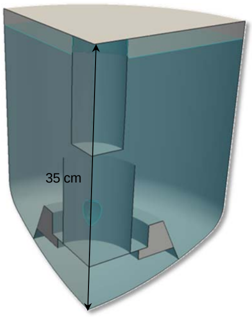
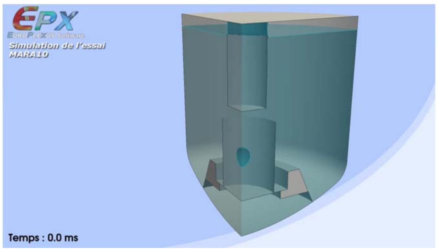
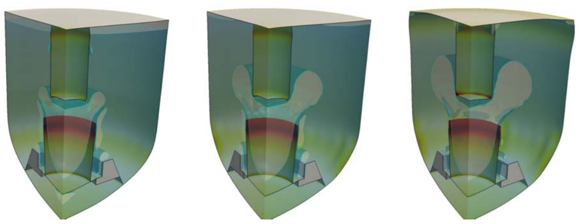
The MARA10 Test
(Courtesy of CEA)



- *Initial conditions*: bubble of ~ **1 cl** at a pressure of **6 250 bar**
- Conforming FSI for the tank and non-conforming for the internal structures
- ALE description of internal fluid grid
- **Interaction between the explosive gas bubble and a cavitation bubble**
- **3D effects** due to the deformation of the tank



Parallelization aspects
(Courtesy of CEA)

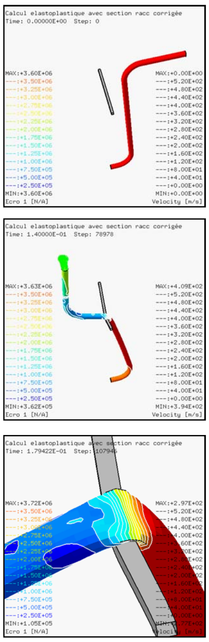


(a) *t* = 1.5 ms (b) *t* = 2.5 ms (c) *t* = 3.5 ms

	Temps écoulé pour 2500 cycles	*Speed-up / 4 proc*	Efficacité
4 processeurs	13939 s		
8 processeurs	5703 s	2.44	1.22
16 processeurs	4035 s	3.45	0.86
32 processeurs	2963 s	4.70	0.59

Interpretation

- Expensive tasks: **construction od FSI connections** and **construction of the global system**
- Data structure effects associated with linked lists
- Availability of **an alternative algorithm for FSI**



Exercise/Example 10 - Pipe Whip

EUROPLEXUS (C) Animation

Pipe Whip Simulation

Author: F. Casadei

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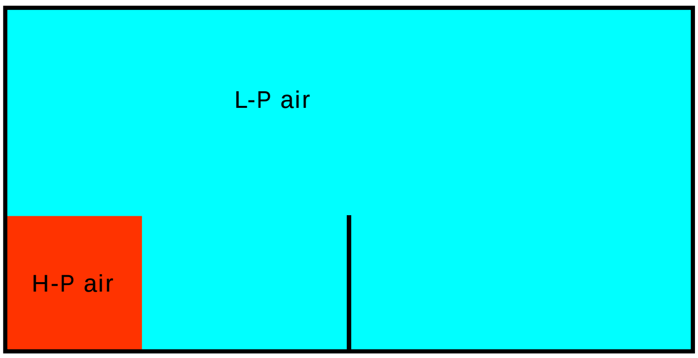
Exercise/Example 10b – Comparison FE/FV

- Compare FE (strong), N-C FV (strong) and C-C FV (weak) in a simple 2D explosion test with conforming F-S mesh



Elasto-plastic structure

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Exercise/Example 10b – Comparison FE/FV (2)

FE

```
…
MATE FLUT RO 5.9485 EINT 4.20274E5 GAMM 1.4
          PB 0 PREF 1.E5 ITER 1 ALF0 1 BET0 1
          KINT 0 AHGF 0 CL 0.5
          CQ 2.56 PMIN 0 NUM 1
          LECT expl TERM
     FLUT RO 1.1897 EINT 2.10137E5 GAMM 1.4
          PB 0 PREF 1.E5 ITER 1 ALF0 1 BET0 1
          KINT 0 AHGF 0 CL 0.5
          CQ 2.56 PMIN 0 NUM 1
          LECT air TERM
…
```

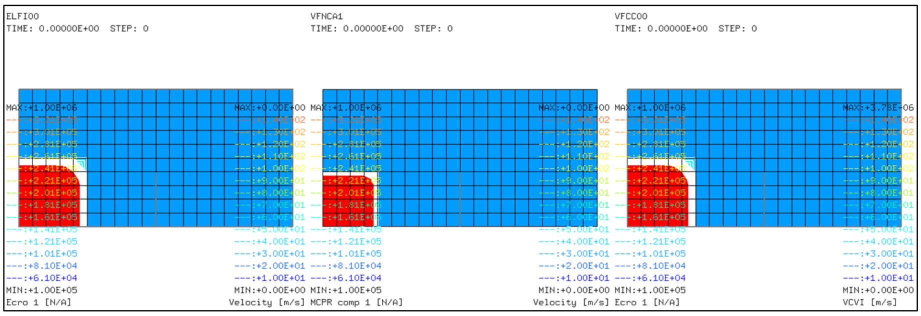
N-C FV

```
…
MATE MCGP NCOM 1 R 8.3143E3
          COMP 'Air' PM 29.0 CV1 2.07585E4
          CV2 0 CV3 0
          LECT flui TERM
     IMPE PIMP RO 1.1897 PRES 1.E5
          LECT pext TERM
…
INIT MCOM COMP 'Air' MFRA 1.0 LECT flui TERM
          PRES 1.E6 LECT expl TERM
          PRES 1.E5 LECT air  TERM
          TEMP 586.36 LECT expl TERM
          TEMP 293.16 LECT air  TERM
          VEL1 0.0 LECT flui TERM
          VEL2 0.0 LECT flui TERM
          VEL3 0.0 LECT flui TERM
…
OPTI MC ORDR 2 NUFL ROE
…
```

C-C FV

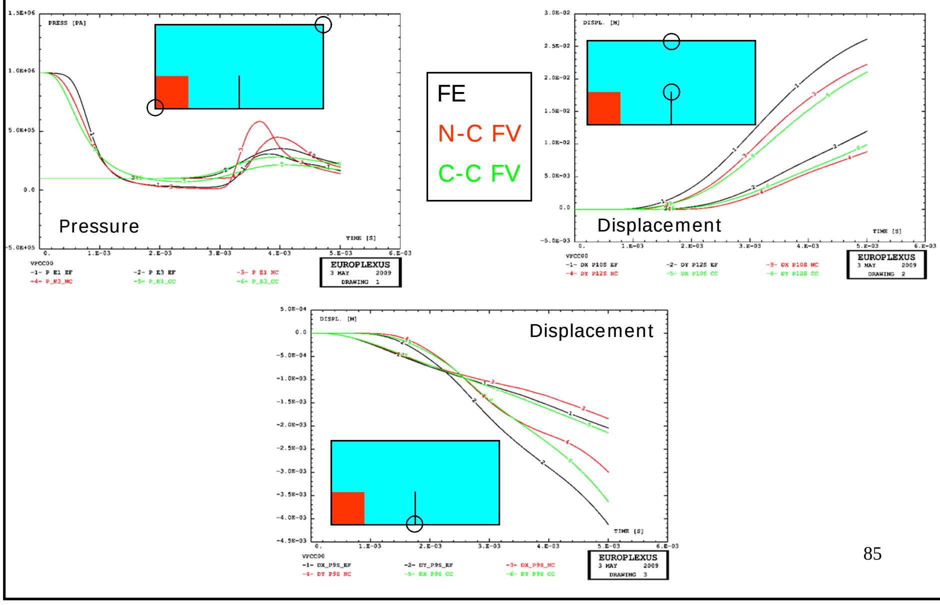
```
…
MATE GAZP RO 5.9485 GAMMA 1.4 CV 716.75
          PINI 1.E6 PREF 1.E5
          LECT expl TERM
     GAZP RO 1.1897 GAMMA 1.4 CV 716.75
          PINI 1.E5 PREF 1.E5
          LECT air TERM
…
OPTI VFCC FCON 1 ! Rusanov
…
```


Exercise/Example 10b – Comparison FE/FV (3)



FE N-C FV C-C FV

Exercise/Example 10b – Comparison FE/FV (4)



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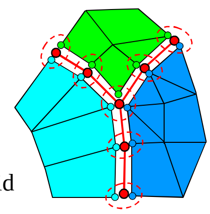
Basic Non-conforming FSI Algorithms



- The FSI algorithms presented so far assumed <u>nodal conformity</u> of F-S interface
- This choice is justified (not too penalizing) in the <u>majority of practical applications</u>, because:
  - ➢ Linear-velocity, uniform-pressure elements used for the fluid
  - ➢ Zero-thickness shells linearly interpolated along membrane
  - ➢ External pressure on shells element-wise uniform
  - ➢ Conformity ensures maximum simplicity and optimal accuracy
- However, the conformity requirement can be removed to obtain an even more general treatment of permanent FSI, which can be very useful in specific advanced applications

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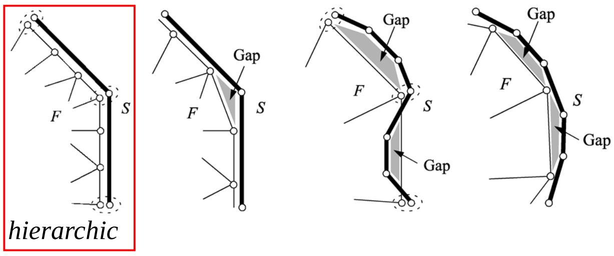
Non-conforming FSI (2)

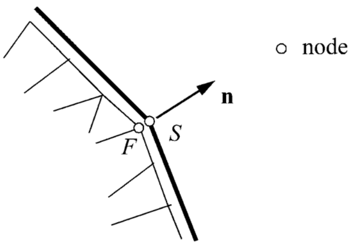
- Tentative classification:

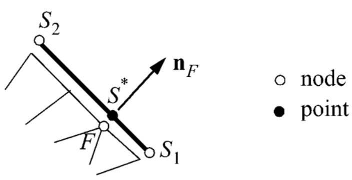


- The hierarchic configuration is the most attractive in practical applications, since the stability step is usually larger in fluid elements than in structural ones (for a given mesh size), and it produces no gaps/overlaps

Non-conforming FSI (3)

- Generalization of coupling (velocity compatibility) conditions:





Matching node *F*

$\boxed{\underline{v}_F \bullet \underline{n} = \underline{v}_S \bullet \underline{n}}$

$\boxed{\underline{w}_F = \underline{w}_S}$

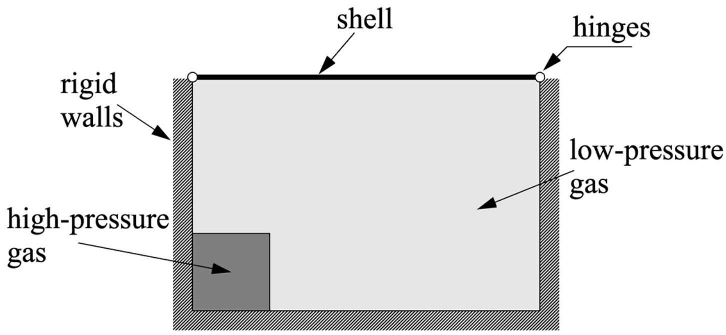
Non-matching node *F*

$\boxed{\underline{v}_F \bullet \underline{n}_F = \underline{v}_{S^*} \bullet \underline{n}_F = (c_1 \underline{v}_{S_1} + c_2 \underline{v}_{S_2}) \bullet \underline{n}_F}$

$\boxed{\underline{w}_F = \underline{w}_{S^*} = c_1 \underline{w}_{S_1} + c_2 \underline{w}_{S_2}}$

$\underline{n}_F$ is the normal to the fluid domain!

Example 4 – Explosion in a 2D box



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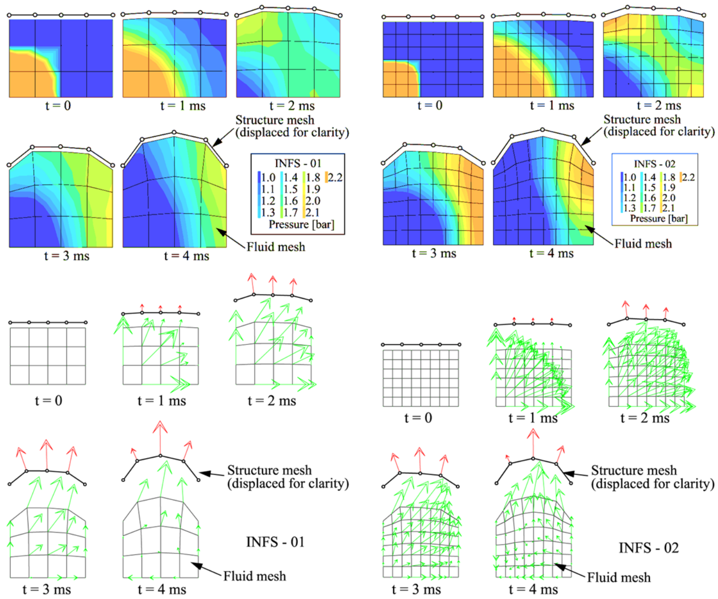
Example 4 – Explosion in a 2D box (2)



A – Conforming B – Non-conforming

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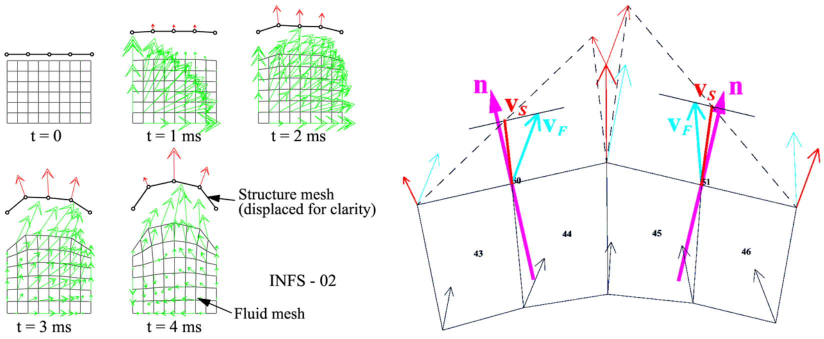
Example 4 – Explosion in a 2D box (3)

Graphical illustration of <u>velocity compatibility condition</u> in the non-conforming case



B – Non-conforming

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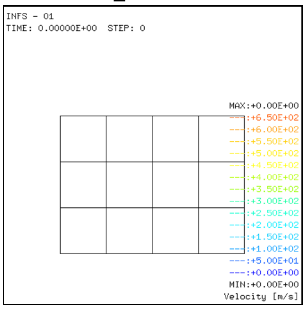
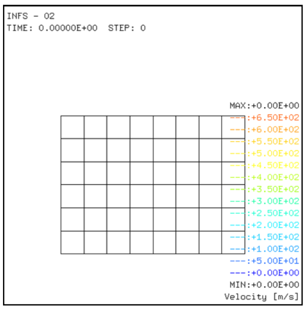
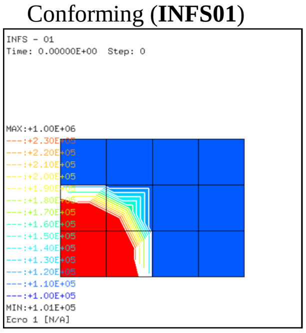
Example 4 – Explosion in a 2D box (4)

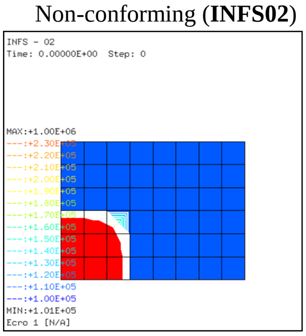




Conforming (**INFS01**)

Non-conforming (**INFS02**)





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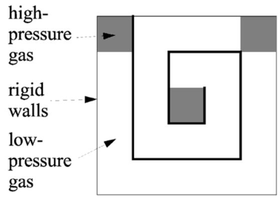
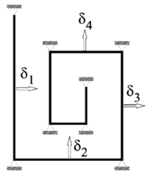
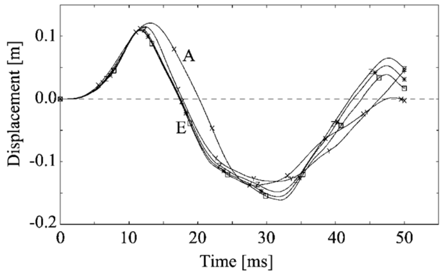
Example 4b – Explosions in a labyrinth



fluid and structure



structure



Labyrinth: displacement δ_1 in cases A to E (progressive mesh refinement)

Case	Mesh refinement Φ (F/S)	Number of elements (F/S)	Time steps	CPU time [s]	CPU time ratio	Speed-up factor
A	1x/1x	100/32	1050	2.6	1.0	-
B	2x/2x	400/64	2100	11.7	4.5	-
C	4x/4x	1600/128	4200	77.5	29.8	-
D	8x/8x	6400/256	8400	587.3	225.9	-
E	16x/16x	25600/512	16789	4747.7	1826.0	-
F	8x/1x	6400/32	1416	110.1	42.3	5.3
G	16x/2x	25600/64	3063	933.7	359.1	5.1
H	16x/1x	25600/32	3087	960.2	369.3	4.9

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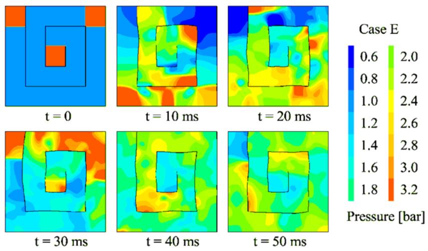
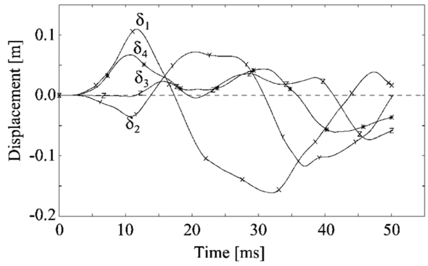
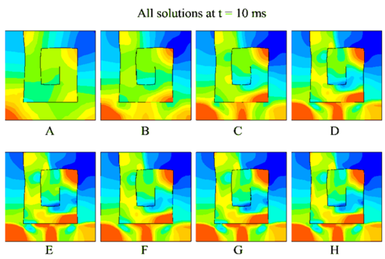
Example 4b – Explosions in a labyrinth (2)



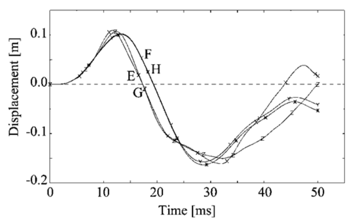
Labyrinth: fluid pressures in case E (reference solution)



Labyrinth: displacements δ_1 to δ_4 in case E (reference solution)



Labyrinth: fluid pressures at 10 ms in all test cases



Labyrinth: displacement δ_1 in cases E (reference) to H (nonconforming mesh solutions)

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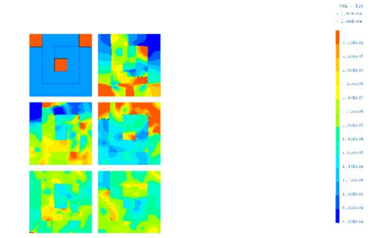
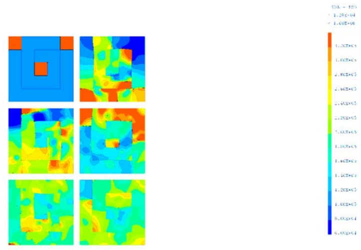
Example 4b – Explosions in a labyrinth (3)

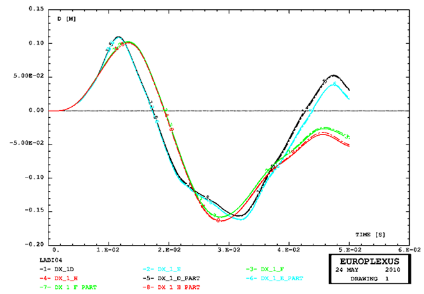


H



H + Partitioning

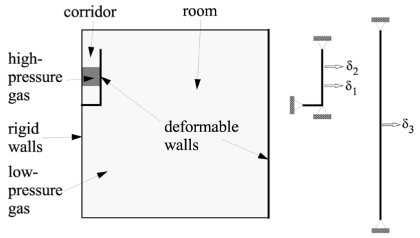
A speed-up of about 2 is achieved by partitioning in these calculations

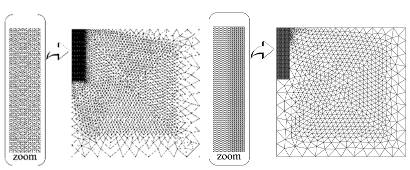


With or without Partitioning

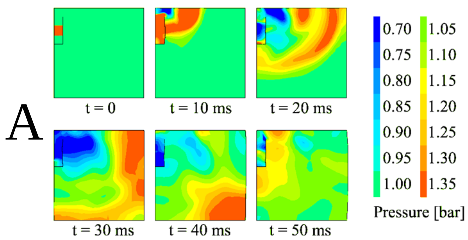
95

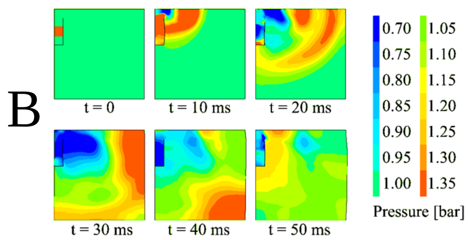
Example 5 – Explosion in a corridor





A – Conforming B – Non-conforming



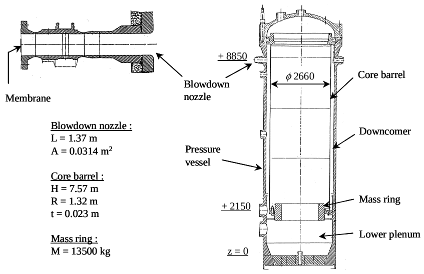


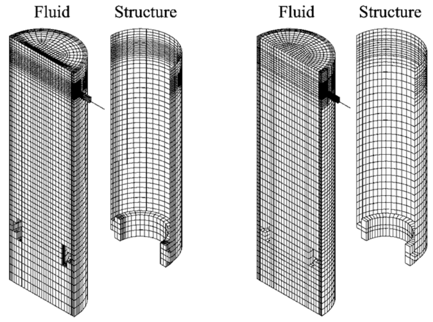
Case	Mesh refinement Φ (F/S)	Number of elements (F/S)	Time steps	CPU time [s]	CPU time ratio	Speed-up factor
A	16x/16x	5497/74	8400	334.7	1.00	-
B	16x/1x	3513/14	1437	39.1	0.12	8.6

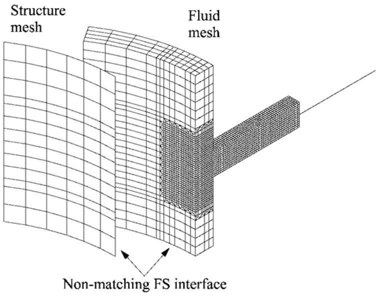
96

Example 6 – LOCA in the HDR

(Courtesy of EDF)







Case	Mesh type	Number of elements (F/S)	Time steps	CPU time [s]	CPU time ratio	Speed-up factor
A	Conforming	35854/2080	41981	83936	1.00	-
B	Nonconforming	34204/1148	15269	22131	0.26	3.8

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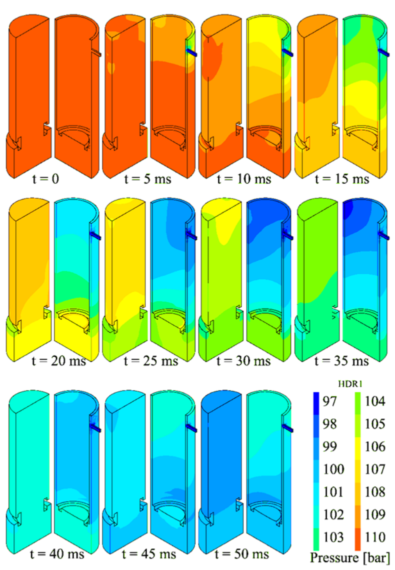
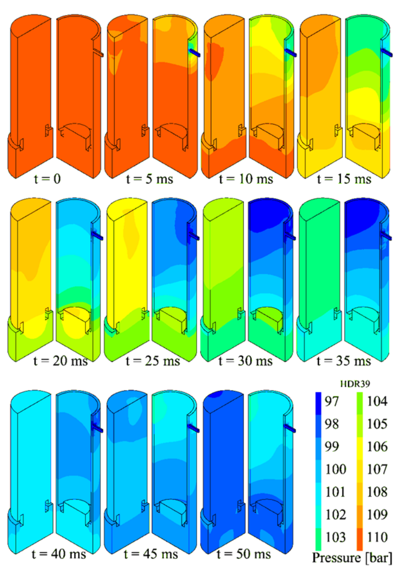
Example 6 – LOCA in the HDR (2)



A – Conforming



B – Non-conforming

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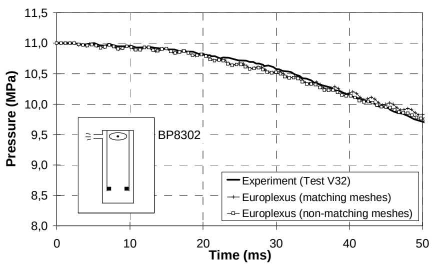
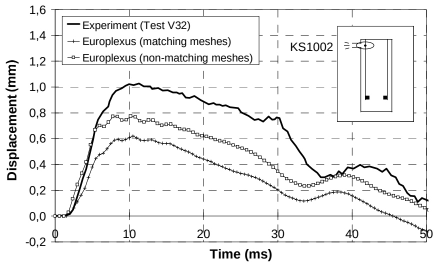
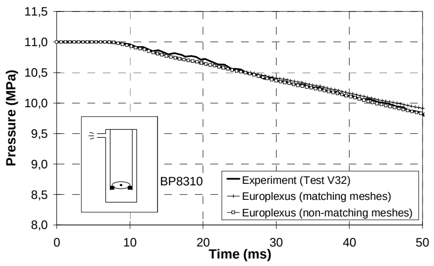
Example 6 – LOCA in the HDR (3)



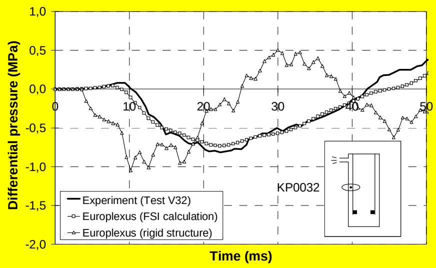
Upper core pressure



Core barrel radial displacement



Lower core pressure

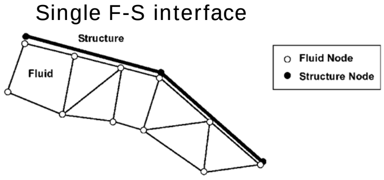


FSI effect on differential pressure

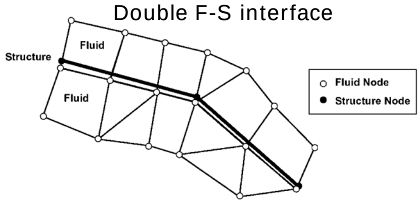
Non-conforming "weak" FSI with CCFV

- The non-conforming FSI algorithms presented above can be applied also to CCFV, but only via a "weak" treatment (pressure) for the moment

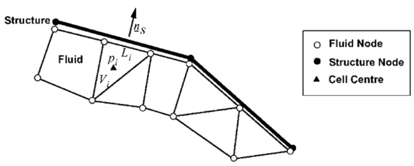
Single F-S interface

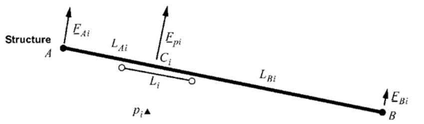


Double F-S interface



- Cell-centered fluid pressures are applied to the structure as shown below, as long as the structure is not failed. Fluxes are **not** computed across a neighboring (unfailed) structure. Matching nodes <u>can be merged or not</u>

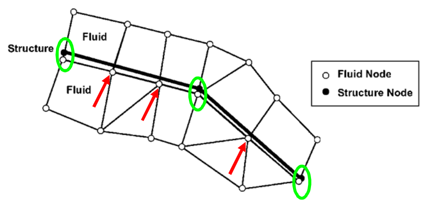




$$E_{Ai} = \frac{L_{Bi}}{L_{Ai}+L_{Bi}}E_{pi} = \frac{L_{Bi}}{L_S}E_{pi} \quad ; \quad E_{Bi} = \frac{L_{Ai}}{L_{Ai}+L_{Bi}}E_{pi} = \frac{L_{Ai}}{L_S}E_{pi} .00$$

Non-conforming “weak” FSI with CCFV (2)

- The matching nodes **can** be merged **or not** (irrelevant)



Couple of matching nodes

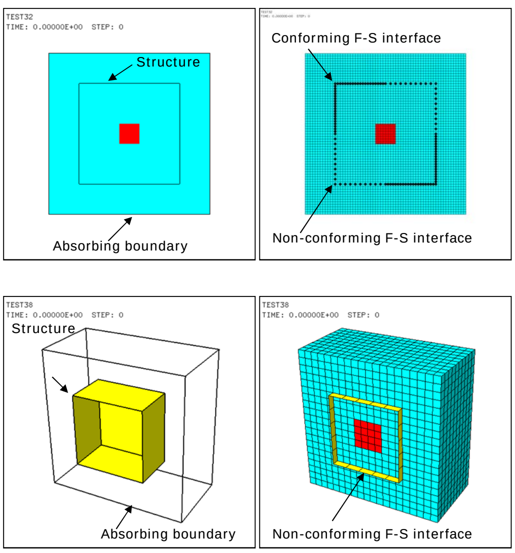
Non-matching fluid node

- The non-matching <u>fluid</u> nodes **must** be declared in a list:

OPTI VFCC ... NCFS /LECT/

Example 6bis – Non-conforming FSI with CCVF

(Weak coupling, without or with structural failure)



2D case

(the dots indicate the structure nodes)

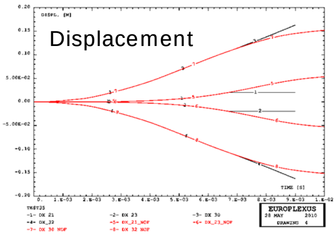
3D case

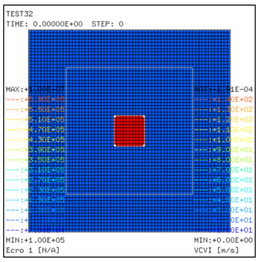
(half model shown for clarity)

Example 6bis – Non-conforming FSI with CCVF (2)

(Weak coupling, without or with structural failure)

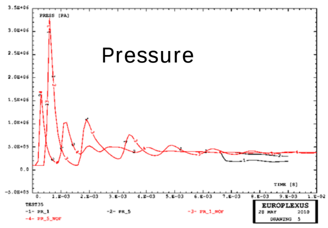
- 2D case :

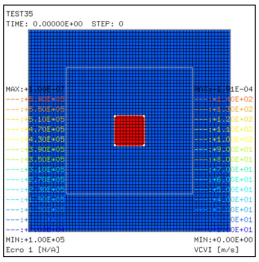




No failure

Comparison





Failure

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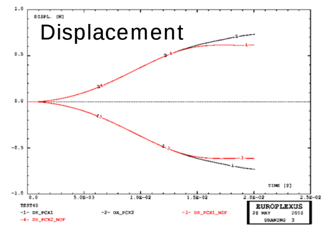
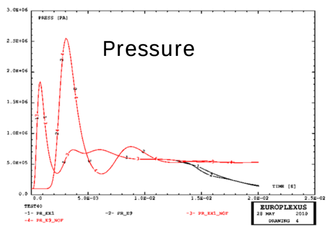
Example 6bis – Non-conforming FSI with CCVF (3)

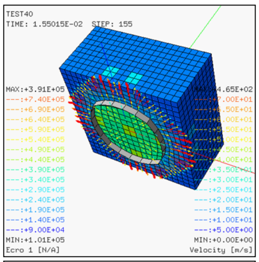
(Weak coupling, without or with structural failure)

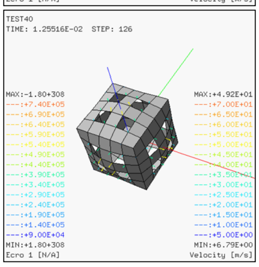
- 3D case :



No failure
Failure







Case with failure

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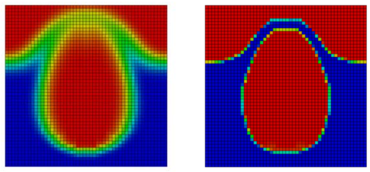
Anti-diffusion (VOFIRE) and FSI

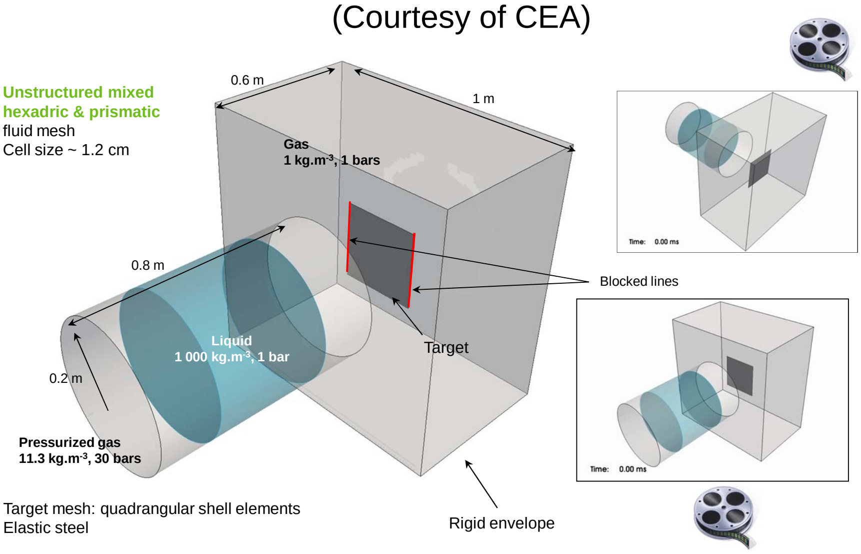


The anti-diffusion techniques presented in Part II (DPLG, VOFIRE) for purely fluid calculations can be very useful also in FSI problems. Some examples are given below.

"Water cannon" on deformable plate

(Courtesy of CEA)

Unstructured mixed hexadric & prismatic fluid mesh
Cell size ~ 1.2 cm

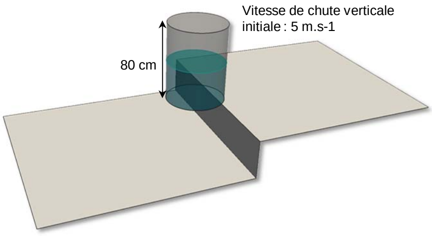


Target mesh: quadrangular shell elements
Elastic steel

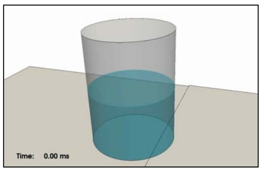
Coupled Euler-Lagrange FSI

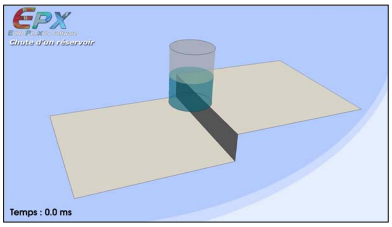
Internal sloshing in a falling tank

(Courtesy of CEA)



- Conforming FSI between the tank (elasto-plastic material) and the internal fluid
- Demonstration of **large rotations management in the automatic motion of the ALE fluid grid**
- **Dynamics of weak flow:**
  - Coarse fluid mesh in 3D (mesh size ~ 1 cm)
  - Gravity flow after rotation
- Expensive calculation (many time steps)





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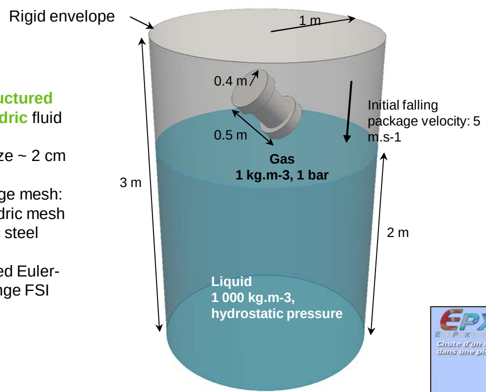
Packaging dropped into a pool

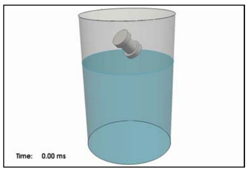
(Courtesy of CEA)

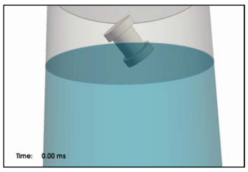
Unstructured hexaedric fluid mesh
Cell size ~ 2 cm

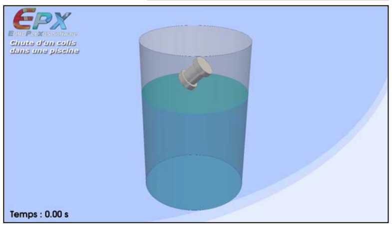
Package mesh: hexaedric mesh
Elastic steel

Coupled Euler-Lagrange FSI



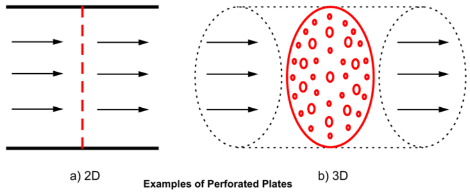






Special FSI Techniques/Applications (1)

- Modeling of perforated structures



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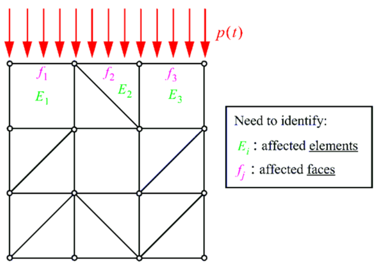
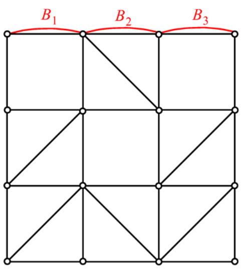
Boundary Condition Elements: CLxx

- Typical example: an externally applied pressure

❑ Use Loading directive (cumbersome!): CHAR 1 FACT 2 PRES FACE ifac p0 /LECT/



❑ Use special CLxx element with IMPE PIMP material:



B_i : C.L. elements (mesh)

The type of boundary condition is specified by assigning to the C.L. element a special "impedance" material: pressure, absorbing, safety valve, grid, ...

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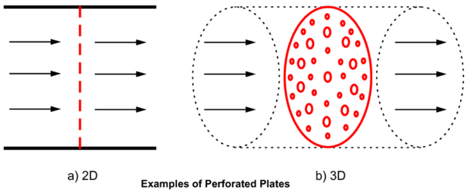
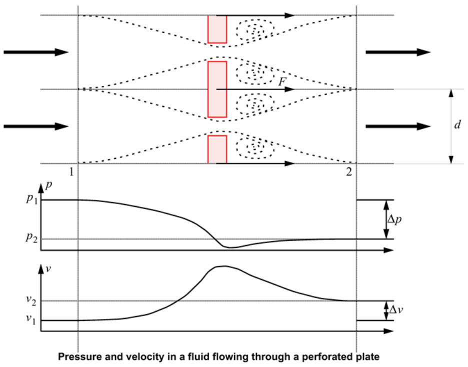
Boundary Condition Elements: CLxx (2)

- More complex example: perforated structures



Examples of Perforated Plates

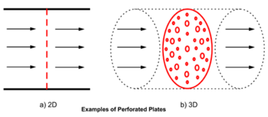
Geometry



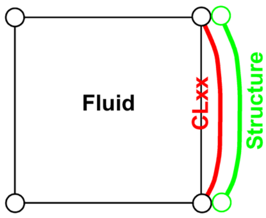
Pressure and velocity in a fluid flowing through a perforated plate

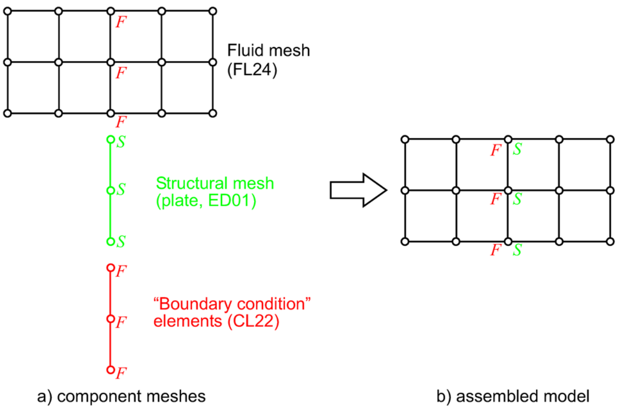
Complex physical behaviour

Boundary Condition Elements: CLxx (3)



Geometry

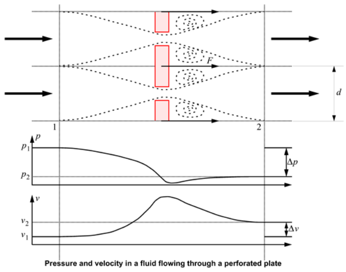




Model by means of CLxx

Modeling of a perforated plate

Boundary Condition Elements: CLxx (4)


Pressure and velocity in a fluid flowing through a perforated plate

Complex physical behaviour

Simplified model: `MATE IMPE PPLA ZETA zeta /LECT/`

$$\Delta p_{12} = \zeta \rho_1 \frac{v_1^2}{2}$$

ζ = resistance coefficient (constant)

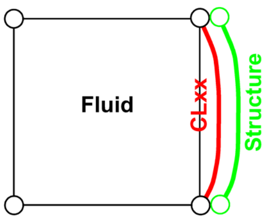
ρ_1 = density upstream (undisturbed region)

v_1 = relative velocity upstream (undisturbed)

$$\Delta p_{12} = \zeta \rho_1 \frac{|v_1| v_1}{2}$$

to account for sign effects

Boundary Condition Elements: CLxx (5)



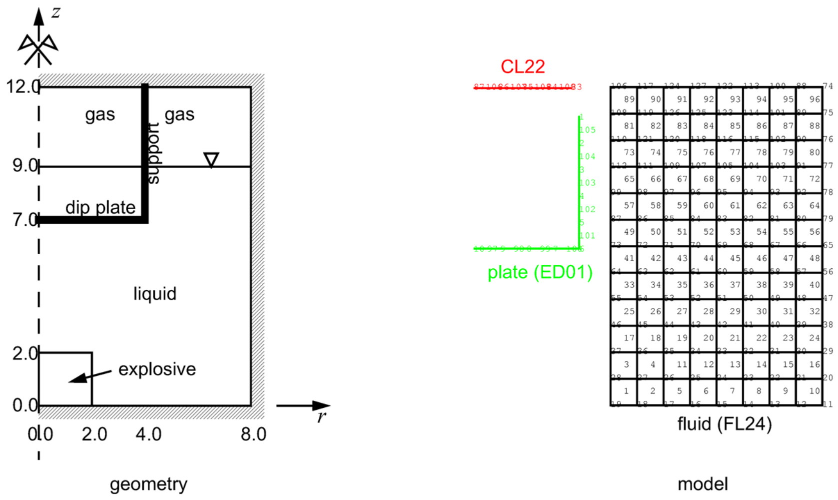
The model is <u>implemented</u> as follows:

*1. For each element CLxx representing a pressure drop across a perforated plate, search the structural node **S** corresponding to each node **F** of the element, and store this information in internal variables of the element;*

*2. When calculating 'internal' forces for such an element, evaluate first the pressure drop **Δp** across the element as a function of fluid and possibly plate velocity. Then, compute the nodal forces generated by this pressure drop: add these forces to the fluid nodes and subtract them from the structural nodes;*

*3. When calculating grid velocities for the ALE fluid nodes, assign to each fluid node **F** the same velocity as the corresponding structural node **S**.*

Exercise/Example 11 – Perforated Plate



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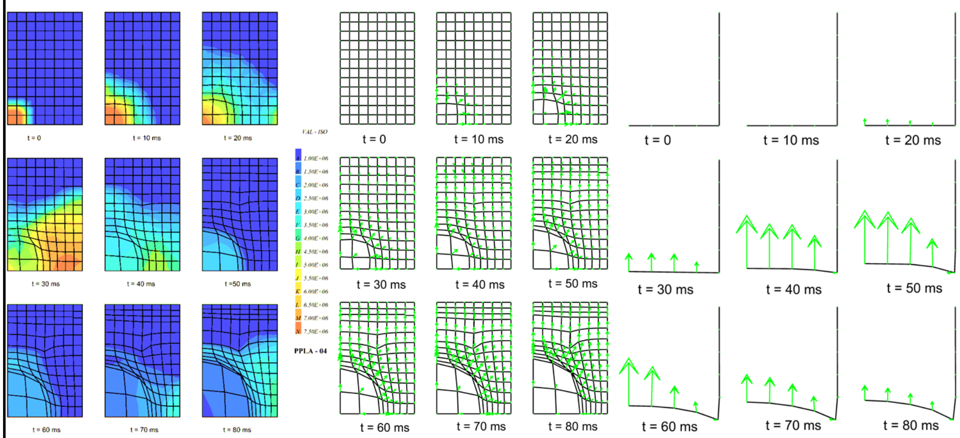
Exercise/Example 11 – Perforated Plate (2)



Pressures *Fluid velocities* *Structure velocities*

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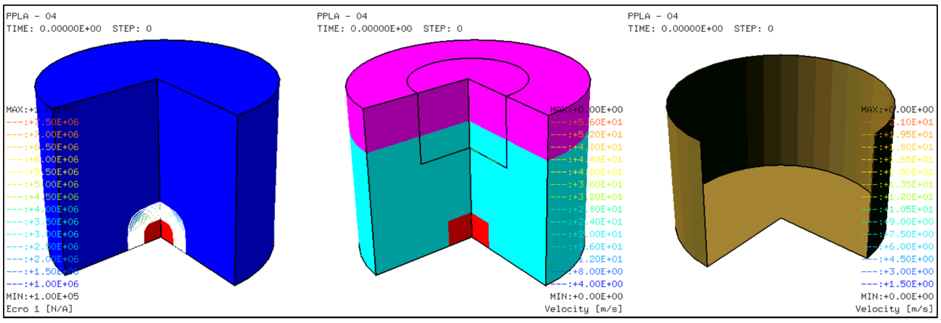
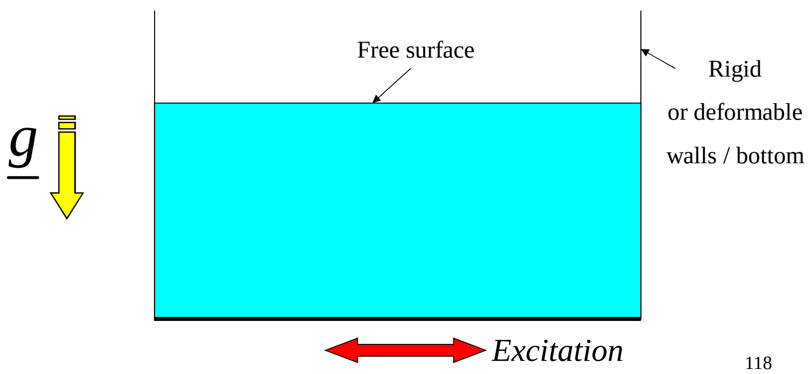
Exercise/Example 11 – Perforated Plate (2)



Pressures *Fluid velocities* *Structure velocities*

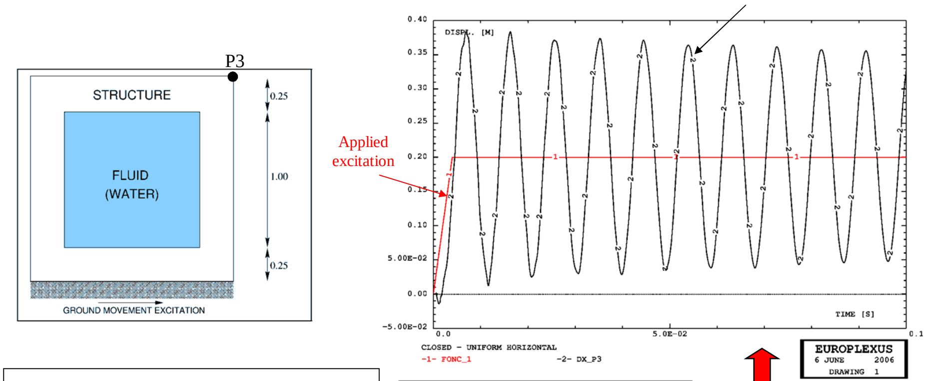
Special FSI Techniques/Applications (2)

- Modeling of tank sloshing phenomena



Exercise/Example 12 – Sloshing (Courtesy of CRS4)

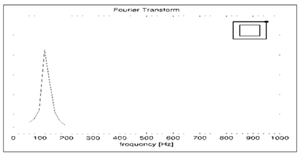
• A - Vibration of a completely filled container:



Bermudez & Rodriguez, 1999:

• 1st mode frequency : 117 Hz

• Estimated frequency : 102 Hz



Computed frequency: 106 Hz

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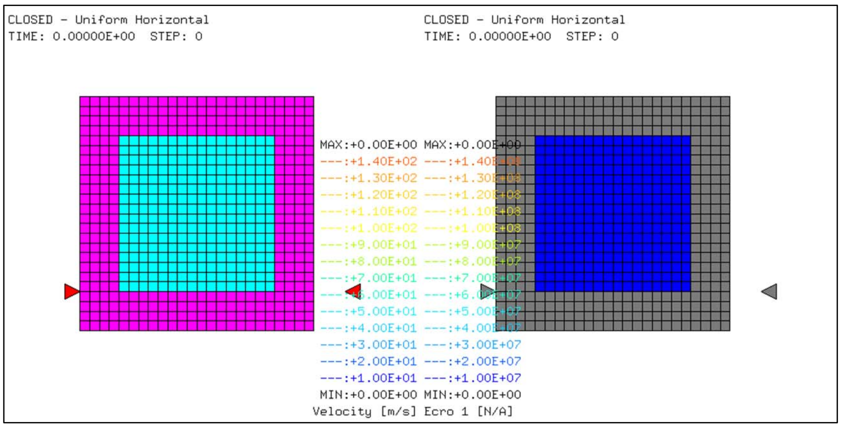
Exercise/Example 12 – Sloshing (2)

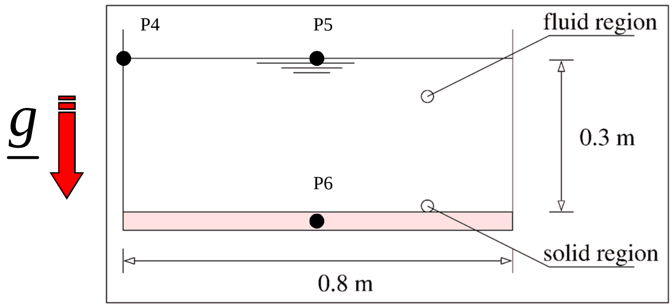


Velocity *Fluid pressure*

120

Exercise/Example 12 – Sloshing (3) (Courtesy of CRS4)

- B - Vibration of a partially filled container:



- Excitation : gravity starting at initial time

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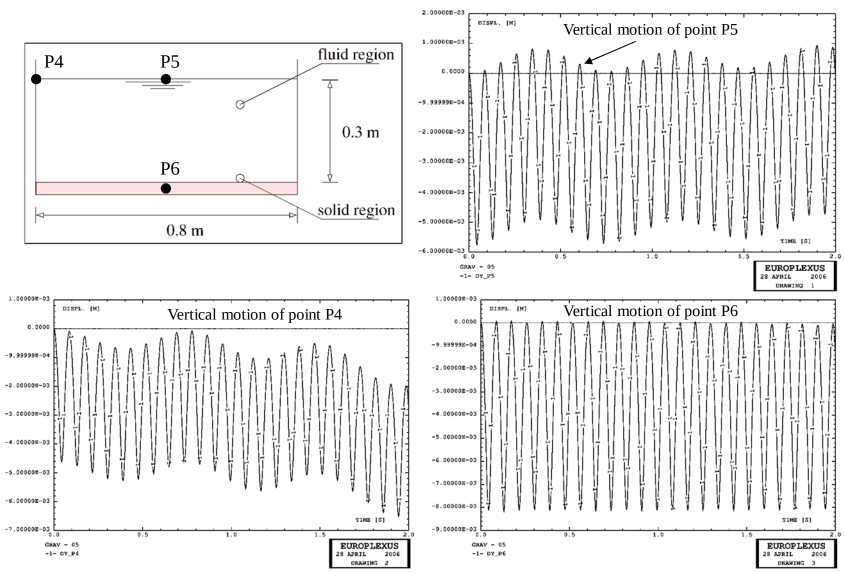
Exercise/Example 12 – Sloshing (4)



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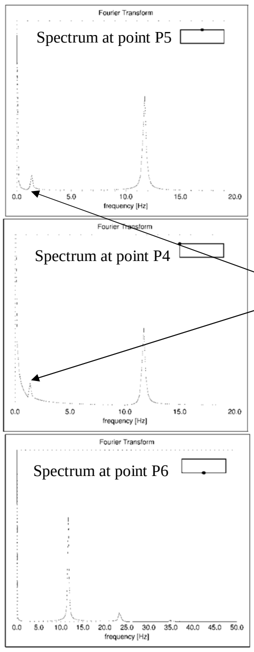

Exercise/Example 12 – Sloshing (5)

- All nodes have a harmonic component at 11.7 Hz
- Surface nodes have, in addition, a lower harmonic component at 1.3 Hz
- Linear theory predicts first symmetric sloshing mode at 1.41 Hz for a rigid tank
- As expected, flexible bottom somewhat reduces the value of the first sloshing frequency

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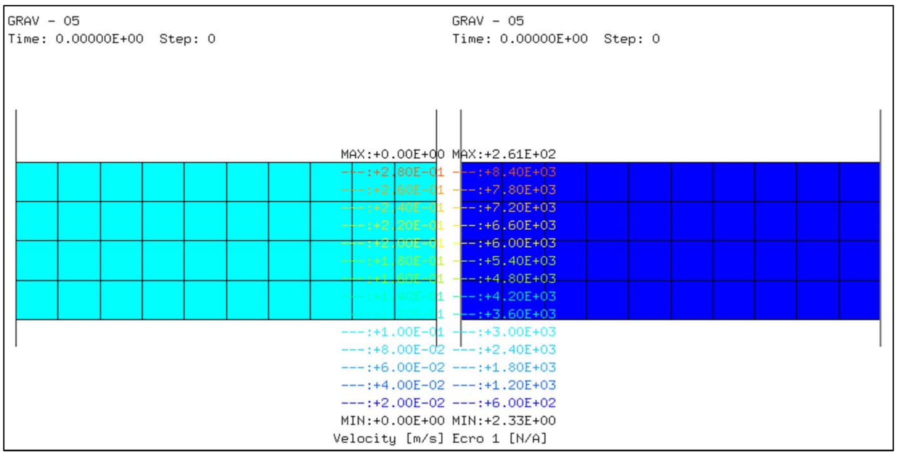
Exercise/Example 12 – Sloshing (6)



Velocity *Fluid pressure*

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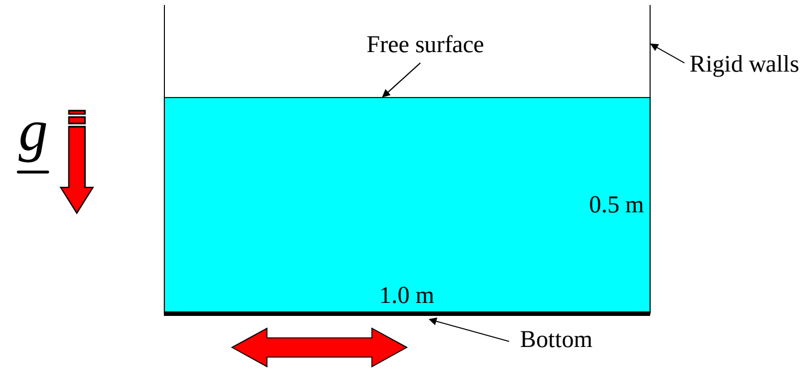
Exercise/Example 12 – Sloshing (7) (Courtesy of CRS4)

- C - Vibration of a partially filled container:



- Excitation : imposed harmonic horizontal displacement
- Container bottom can be either rigid or flexible

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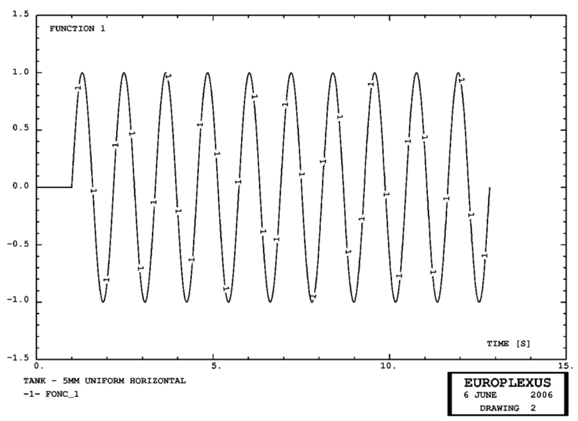
Exercise/Example 12 – Sloshing (8) (Courtesy of CRS4)

- First sloshing frequency (linear theory) is 5.316 Hz
- Excitation frequency is 5.311 Hz, amplitude 9.3 mm, starting at t = 1 s



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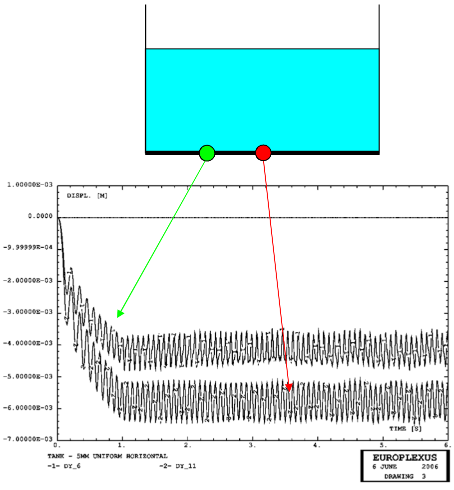
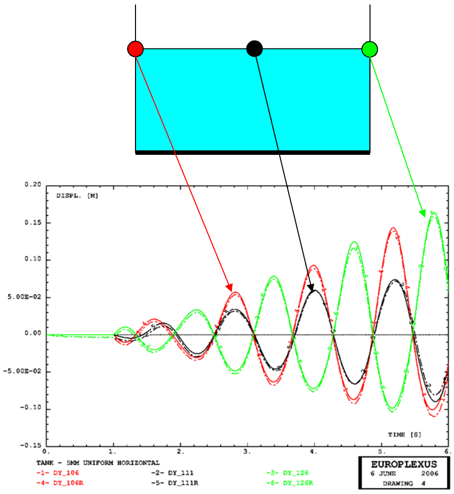
Exercise/Example 12 – Sloshing (9) (Courtesy of CRS4)



Displacement of bottom (flexible case)



Displacement of free surface (solid=rigid, dashed=flexible)

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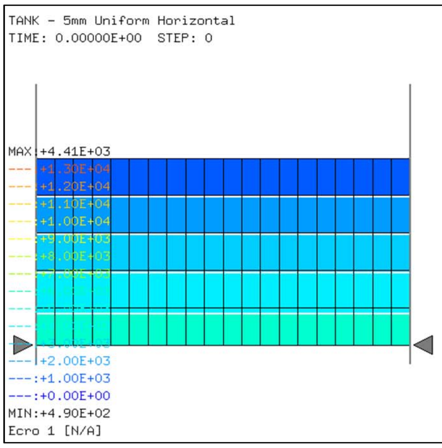
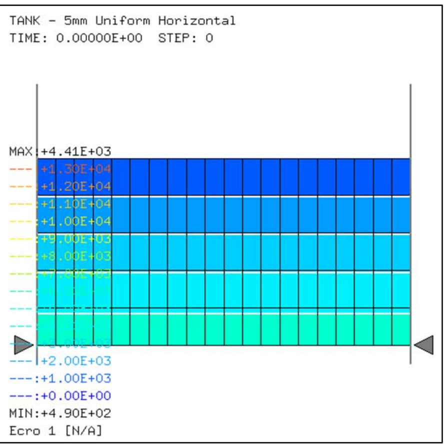
Exercise/Example 12 – Sloshing (10)



Pressure, rigid bottom



Pressure, flexible bottom

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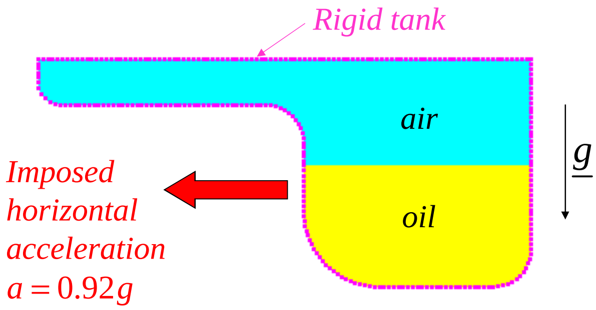
Exercise/Example 12 – Sloshing (11)

(Courtesy of Samtech)

- D – Accelerated oil cup:



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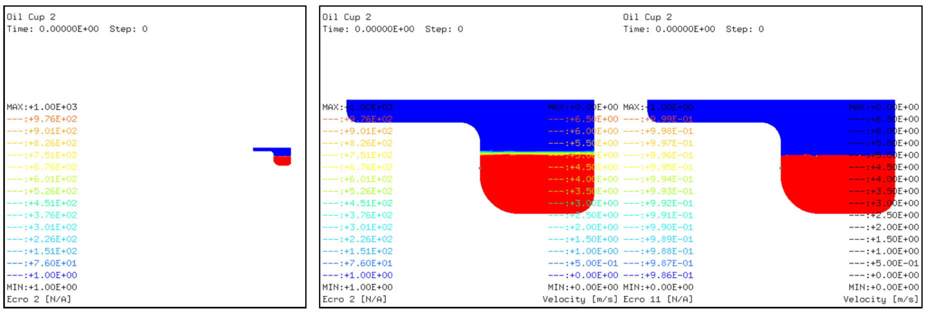
Exercise/Example 12 – Sloshing (12)



Density *Density* *Oil mass fraction*

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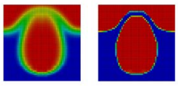
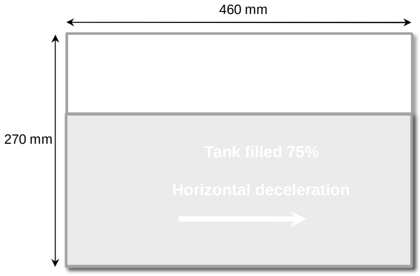
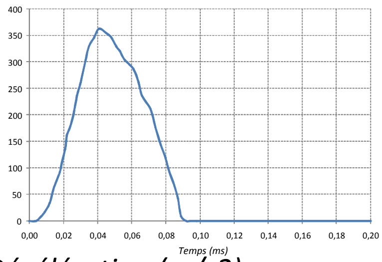


Sloshing in a decelerated tank with anti-diffusion (Courtesy of CEA)

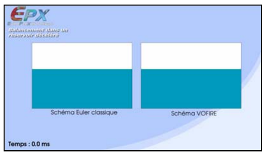




Décélération (m/s2)

Experimental results (Yamaha, 1988)

Form of the gas volume during the transient



Numerical simulations

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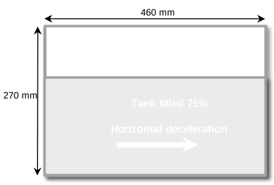
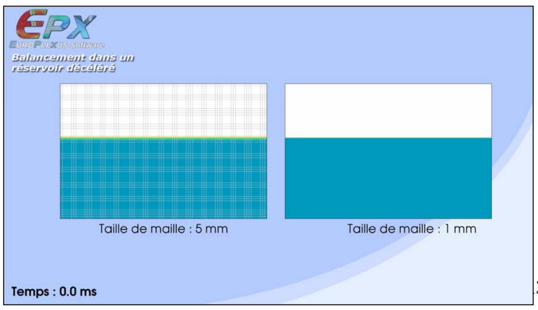
Sloshing in a decelerated tank

(Courtesy of CEA)



- Dynamic phenomenon driven by the **conversion of a slight overpressure, due to deceleration, in velocity along the walls**
- Need for precision and regularity of the pressure field
- **Strong pressure oscillations along the interface due to the mixing model**
- Large oscillations near the interface (checkerboarding effect)



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