Annals of Nuclear Energy 82 (2015) 188–194

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Hybrid parallel strategy for the simulation of fast transient accidental situations at reactor scale

V. Faucher [a,b,*], P. Galon [a,b], A. Beccantini [c], F. Crouzet [b,d], F. Debaud [e], T. Gautier [f]

[a] CEA, DEN, DANS, DM2S, SEMT, DYN, Gif sur Yvette F-91191, France
[b] LaMSID, UMR EDF-CEA-CNRS 2832, Clamart F-92141, France
[c] CEA, DEN, DANS, DM2S, STMF, LATF, Gif sur Yvette F-91191, France
[d] EDF R&D, Analysis in Mechanics and Acoustics, Clamart F-92141, France
[e] EDF, Service Etudes et Projets Thermiques et Nucléaires, Villeurbanne F-69628, France
[f] INRIA, EPI MOAIS, Laboratoire d'Informatique de Grenoble, Montbonnot Saint Martin F-38330, France

ARTICLE INFO

Article history:
Received 18 April 2014
Accepted 31 July 2014
Available online 22 August 2014

Keywords:
Large scale fluid-structure systems
Fast transient accidental situations
Hybrid parallel solver

ABSTRACT

This contribution is dedicated to the latest methodological developments implemented in the fast transient dynamics software EUROPLEXUS (EPX) to simulate the mechanical response of fully coupled fluid–structure systems to accidental situations to be considered at reactor scale, among which the Loss of Coolant Accident, the Core Disruptive Accident and the Hydrogen Explosion.

Time integration is explicit and the search for reference solutions within the safety framework prevents any simplification and approximations in the coupled algorithm: for instance, all kinematic constraints are dealt with using Lagrange Multipliers, yielding a complex flow chart when non-permanent constraints such as unilateral contact or immersed fluid–structure boundaries are considered. The parallel acceleration of the solution process is then achieved through a hybrid approach, based on a weighted domain decomposition for distributed memory computing and the use of the KAAPI library for self-balanced shared memory processing inside subdomains.

1. Element of context

The transient mechanical consequences of three reference accidents for current and future nuclear reactors are considered. Due to fully coupled fluid–structure mechanics, they all share the need for a simulation at the full reactor scale, yielding large fluid–structure systems and numerous kinematic constraints.

The accidents are named and shortly described on Table 1.

The present contribution introduces the parallel solution strategy implemented in EUROPLEXUS (EPX, http://www-epx.cea.fr) fast transient dynamics software for the kind of simulations introduced above, elaborated in collaboration with INRIA through the ANR RePDyn project (http://www.repdyn.fr).

2. Numerical methods

2.1. Local equations

The following set of local equations is considered:

Dynamic equilibrium for structures
$$\rho\ddot{\mathbf{q}} + \nabla\cdot\{\boldsymbol{\sigma}[\boldsymbol{\varepsilon}(\mathbf{q})]\} = \mathbf{f}_{vol}^{str} \quad (1\text{-a})$$

Momentum conservation for fluids
$$\rho\dot{\mathbf{u}} + \nabla P + \rho\mathbf{u}\cdot\nabla\mathbf{u} = \mathbf{f}_{vol}^{flu} \quad (1\text{-b})$$

Mass conservation for fluids
$$\dot{\rho} + \nabla\cdot(\rho\mathbf{u}) = 0 \quad (1\text{-c})$$

Total energy conservation for fluids
$$\dot{E} + \nabla\cdot[\mathbf{u}(E+P)] = 0 \quad (1\text{-d})$$

The description is Lagrangian for structures and Eulerien/ALE for fluids.

The momentum conservation equation is written in its non-conservative form, since it makes it easier to exhibit the fluid–structure forces. Anyway, a fully conservative formalism is also available in EPX (and used for example for the simulation of the Hydrogen Explosion).

These equations are completed by a set of kinematic constraints, expressing between structural entities (for example through unilateral contact) or between structural and fluid entities. Theses constraints, variable with both time and space, have the general form:

* Corresponding author at: CEA, DEN, DANS, DM2S, SEMT, DYN, Gif sur Yvette F-91191, France.
E-mail address: vincent.faucher@cea.fr (V. Faucher).

http://dx.doi.org/10.1016/j.anucene.2014.07.049
0306-4549/

Table 1
Considered accidental situations.

Accident	Short description	Characteristics of the simulation
Loss Of Coolant Accident	Large breach and fluid leak in the high pressure primary loop, high level rarefaction wave propagation	Coupled 1D-models for pipe loops and 3D-models for the main vessel, fluid–structure interaction and impedances for correct wave propagation, multi-phase water flow
Core Disruptive Accident	Expansion of a high pressure bubble in a pool inside a vessel with free surface and complex immersed structures	Fluid–structure interaction with immersed boundaries, interface tracking, multi-component flow
Hydrogen Explosion	Reaction of a mix of dioxygen and dihydrogen in a nuclear containment building after a nuclear power excursion	Reactive flows, accurate robust models for deflagration and detonation regimes, fluid–structure interaction

$$\mathbf{C}(\mathbf{q},\mathbf{u}) = \mathbf{S} \tag{2}$$

2.2. Time and space discretization

Time discretization is achieved through the central difference scheme for structures and through the forward Euler scheme for fluids, i.e.:

$$\begin{aligned}\dot{\mathbf{q}}^{n+1/2} &= \dot{\mathbf{q}}^{n-1/2} + \Delta t\ddot{\mathbf{q}}^{n}\\ \mathbf{q}^{n+1} &= \mathbf{q}^{n} + \Delta t\dot{\mathbf{q}}^{n+1/2}\\ \mathbf{u}^{n+1} &= \mathbf{u}^{n} + \Delta t\dot{\mathbf{u}}^{n}\end{aligned} \tag{3}$$

Space discretization is achieved through Finite Elements for structures. For fluids, a Finite Volume approach is always used for the mass and total energy conservation equations. For the momentum conservation equations, a Finite Element approach is implemented for the Core Disruptive Accident and the Loss of Coolant Accident, whereas a Finite Volume approach is used for the Hydrogen Explosion. The choice of the method as well as the details of the implemented Finite Volume schemes is not discussed in the present contribution.

The discrete system to consider at each time step takes the general form (with Finite Elements for the momentum conservation):

$$\begin{aligned}&\begin{bmatrix}\mathbf{M}_S & \\ & \mathbf{M}_F^{n+1}\end{bmatrix}\begin{bmatrix}\ddot{\mathbf{Q}}^{n+1}\\ \dot{\mathbf{U}}^{n+1}\end{bmatrix} + \mathbf{F}_{\text{link}}^{n+1} = \begin{bmatrix}\mathbf{F}_{\text{ext}}^{\text{str}}\\ \mathbf{F}_{\text{ext}}^{\text{flu}}\end{bmatrix}^{n+1} - \begin{bmatrix}\mathbf{F}_{\text{int}}(\mathbf{Q}^{n+1})\\ \mathbf{F}_{\text{P}}(\mathbf{U}^{n+1}) + \mathbf{F}_{\text{trans}}(\mathbf{U}^{n+1})\end{bmatrix}\\ &\mathbf{C}^{n+1}\begin{bmatrix}\dot{\mathbf{Q}}^{n+3/2}\\ \mathbf{U}^{n+2}\end{bmatrix} = \mathbf{S}^{n+1}\\ &[\rho]^{n+1} = [\rho]^{n} + \mathbf{F}_{\rho}(\mathbf{U})\\ &[E]^{n+1} = [E]^{n} + \mathbf{F}_{\text{E}}(\mathbf{U})\end{aligned} \tag{4}$$

Mass matrices $\mathbf{M}_S$ and $\mathbf{M}_F^{n+1}$ are made diagonal by classical lumping techniques. $\mathbf{F}_\rho$ and $\mathbf{F}_E$ are Finite Volume fluxes through the faces of the fluid cells. $\mathbf{C}^{n+1}$ and $\mathbf{S}^{n+1}$ are the discrete kinematic constraints operator and right hand side, acting on the next mid-step velocity for structures and on the next full step velocity for fluids.

2.3. Kinematic constraints management

Kinematic constraints are handled either by direct methods when possible (for example, fluid–structure interaction with Finite Volumes) or through a dual approach, using Lagrange Multipliers to compute the coupling forces $\mathbf{F}_{\text{link}}^{n+1}$.

In both cases, no arbitrary parameter is allowed to enforce the constraints (such as penalty coefficients).

In the case of the dual approach with Lagrange Multipliers, the system to solve is thus:

$$\begin{aligned}&\begin{bmatrix}\mathbf{M}_S & \\ & \mathbf{M}_F^{n+1}\end{bmatrix}\begin{bmatrix}\ddot{\mathbf{Q}}^{n+1}\\ \dot{\mathbf{U}}^{n+1}\end{bmatrix} + {}^t\tilde{\mathbf{C}}^{n+1}\Lambda = \begin{bmatrix}\mathbf{F}_{\text{vol}}^{\text{str}}\\ \mathbf{F}_{\text{vol}}^{\text{flu}}\end{bmatrix}^{n+1}\\ &-\begin{bmatrix}\mathbf{F}_{\text{int}}(\mathbf{Q}^{n+1})\\ \mathbf{F}_{P}(\mathbf{U}^{n+1}) + \mathbf{F}_{\text{trans}}(\mathbf{U}^{n+1})\end{bmatrix}\tilde{\mathbf{C}}^{n+1}\begin{bmatrix}\ddot{\mathbf{Q}}^{n+1}\\ \dot{\mathbf{U}}^{n+1}\end{bmatrix} = \tilde{\mathbf{S}}^{n+1}\end{aligned} \tag{5}$$

The system is no longer diagonal, which represents a significant computational complexity for explicit fast transient dynamics.

Kinematic constraints are classified as follows, ordered by increasing complexity.

1. *Permanent constraints with constant coefficients*: these are namely boundary conditions or mechanical relations between degrees of freedom.
2. *Permanent constraints with variable coefficients*: they are currently encountered for fluid–structure interaction with conforming meshes.
3. *Non-permanent constraints*: this is the general case, where the constraint operators must be completely built at each time step (see for instance Fig. 1 for the example of fluid–structure interaction with non-conforming meshes).

2.4. Multi-component and reactive flows

2.4.1. Reactive flow for Hydrogen Explosion

A robust approach is implemented to represent reactive flow in both deflagration and detonation regimes, based on the Reactive Discrete Equation Method (Beccantini and Studer, 2010). The main issue for such models is that the characteristic length governing the flame propagation in the deflagration regime is much smaller than the dimensions of the buildings where the explosive

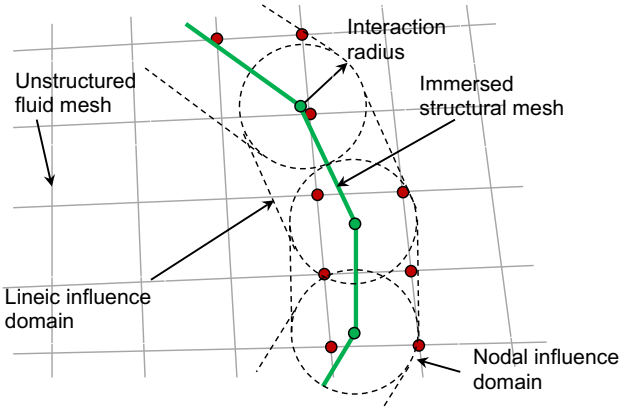

Fig. 1. Fluid–structure interaction for immersed structures.