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Advanced parallel strategy for strongly coupled fast transient fluid-structure dynamics with dual management of kinematic constraints

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ABSTRACT

Simulating fast transient phenomena involving fluids and structures in interaction for safety purposes requires both accurate and robust algorithms, and parallel computing to reduce the calculation time for industrial models. Managing kinematic constraints linking fluid and structural entities is thus a key issue and this contribution promotes a *dual* approach over the classical penalty approach, introducing arbitrary coefficients in the solution. This choice however severely increases the complexity of the problem, mainly due to non-permanent kinematic constraints. An innovative parallel strategy is therefore described, whose performances are demonstrated on significant examples exhibiting the full complexity of the target industrial simulations.

1. Introduction

The present contribution deals with the simulation of complex strongly coupled fluid-structure systems submitted to fast transient loadings, such as high velocity impacts or explosions. Examples of such systems are:

- nuclear vessels with internal immersed structures submitted to an explosion in the vicinity of the core of the reactor,
- rotor blade wheels impacting surrounding stators, which can occur for aeronautic engines or alternators of electric power plants (models with structures only, with couplings coming from numerous contacts, see Section 3.4 for instance),
- many kinds of infrastructures submitted to malevolent acts.

The proposed work is not dedicated to producing quantitative results for the above situations, often strongly confidential, but focuses instead on providing robust, accurate and efficient parallel methods to perform such simulations. The case of distributed memory clusters is considered, since it presents the tightest algorithmic locks and is compulsory to address high numbers of cores (i.e. hundreds to thousands). The proposed strategy is then intended to be associated with a shared memory approach into a hybrid framework, shortly described in Section 5.

A reference fluid-structure algorithm with kinematic constraints, both permanent and non-permanent, is first described in Section 2, based on a rigorous *dual* approach to compute the constraint forces, free from any non-physical parameter, prohibited for analyses performed in a safety environment, but exhibiting a complexity which causes the current parallel strategies for distributed memory clusters to fail as far as explicit time integration is concerned.

An innovative parallel algorithm is thus mandatory to overcome the introduced algorithmic locks and one is provided in Section 3, mainly based on a specific distributed solver dedicated to the computation of constraint forces coupling several parallel processes. The large displacements of the structures submitted to high energy transient loadings are also taken into account by replacing the static initial distribution of the data onto the available processes by an updated domain decomposition.

The performances of the proposed parallel strategy are demonstrated in Section 3 through two specifically chosen examples, the first with only permanent kinematic constraints and the second containing only structures but with very large relative displacements between the structural bodies, as well as failure, fragmentation and generalized contact. Section 4 is finally dedicated to the implementation of the complete methodology on a fully coupled fluid-structure system.

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Nomenclature

ρ	local density for structures and fluid	E	fluid total energy
$\mathbf{q}$	structural displacement	$\mathbf{f}_{\text{vol}}^{\text{str}}$	structural body forces
$\boldsymbol{\sigma}$	structural Cauchy stress tensor	$\mathbf{f}_{\text{vol}}^{\text{flu}}$	fluid body forces
$\boldsymbol{\varepsilon}$	structural Almansi–Euler strain tensor		
u	fluid velocity		
P	fluid pressure		

2. Fast transient fluid-structure dynamics with strong kinematic couplings

2.1. Local equations

The considered fluid-structure systems are governed by the following set of local equations [1] (see the nomenclature for the meaning of each variable):

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

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

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

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

The description is Lagrangian for the structures and Eulerian for the fluid (or ALE, for *Arbitrary Euler Lagrange*, if the fluid grid has to be updated to follow the displacements of a surrounding structure).

The equations for fluid dynamics are the compressible Euler equations, taking into account that only fast transient simulations are considered (i. e. a typical total physical time from 1 to 100 ms), preventing any conductive or viscous phenomena to establish.

The momentum conservation equation for fluids is written in its non-conservative form, since it provides an easy way to exhibit fluid-structure forces in the spatially discretized system (see Section 2.2). The transport force vector $\mathbf{f}_{\text{trans}}$ accounts for the non-linear convective terms, i. e.:

$$\mathbf{f}_{trans}(\mathbf{u}) = \rho\mathbf{u}\cdot\nabla\mathbf{u} \tag{2}$$

This set is completed by kinematic constraints, expressing the *dirichlet* boundary conditions and couplings between either structural entities (for example, interacting by means of unilateral contact) or fluid and structural entities. A general form of these constraints, variable with time, writes:

$$\mathbf{C}(\mathbf{q},\mathbf{u}) = \mathbf{S} \tag{3}$$

The considered system is fully non-linear:

1. the structural strains tensor is computed from displacement using the Almansi-Euler relation (i. e. the reference configuration is the actual configuration):

$$\boldsymbol{\varepsilon}(\mathbf{q}) = \frac{1}{2}(\nabla\mathbf{q} + {}^{t}\nabla\mathbf{q} - {}^{t}\nabla\mathbf{q}\nabla\mathbf{q}) \tag{4}$$

2. the constitutive relations for structures, giving the stress tensor from the strain tensor, account for many kinds of irreversible phenomena such as plasticity, damage or failure,
3. the kinematic constraints vary with both space and time.

2.2. Time/space discretization and kinematic constraints management

Space discretization is achieved by means of finite elements for the structure. For the fluid, a finite volume approach is always used for the mass and total energy conservations. As far as the momentum conservation is concerned, both finite volume and finite element approximations can be considered, with their own advantages and drawbacks, not discussed in this paper, and little impact of this choice on the parallel strategy described below. The latter finite element approach is preferred in the present case since it allows a more explicit expression of the fluid-structure interaction forces, the fluid velocities being located at the nodes of the fluid mesh. This would also be the case with node-centered polyhedral finite volumes however, coming again with its own specificities in terms of accuracy that shall not be discussed in the present paper, since this choice does not reduce the generality of the algorithmic developments proposed below.

According to the fast transient dynamics context, time integration is carried through the explicit central differences scheme for structures and the explicit forward Euler scheme for fluids, yielding, from the step n to the step $n+1$ of the discrete time scale:

$$\begin{aligned}
\dot{\mathbf{q}}^{n+1/2} &= \dot{\mathbf{q}}^{n-1/2} + \Delta t\ddot{\mathbf{q}}^{n} \\
\mathbf{q}^{n+1} &= \mathbf{q}^{n} + \Delta t\dot{\mathbf{q}}^{n+1/2} \\
\mathbf{u}^{n+1} &= \mathbf{u}^{n} + \Delta t\dot{\mathbf{u}}^{n}
\end{aligned} \tag{5}$$

using the mid-steps to evaluate the structural velocities.

The discrete system to consider at each time step then writes:

$$\begin{aligned}
&\begin{bmatrix} \mathbf{M}_S & \\ & \mathbf{M}_F^{n+1} \end{bmatrix}\begin{bmatrix} \ddot{\mathbf{Q}}^{n+1} \\ \dot{\mathbf{U}}^{n+1} \end{bmatrix} + \mathbf{F}_{\text{link}}^{n+1} = \begin{bmatrix} \mathbf{F}_{\text{vol}}^{\text{str}} \\ \mathbf{F}_{\text{vol}}^{\text{flu}} \end{bmatrix}^{n+1} - \begin{bmatrix} \mathbf{F}_{\text{int}}(\mathbf{Q}^{n+1}) \\ \mathbf{F}_P(\mathbf{U}^{n+1}) + \mathbf{F}_{\text{trans}}(\mathbf{U}^{n+1}) \end{bmatrix} \\
&\mathbf{C}^{n+1}\begin{bmatrix} \dot{\mathbf{Q}}^{n+3/2} \\ \mathbf{U}^{n+2} \end{bmatrix} = \mathbf{S}^{n+1} \\
&[\rho]^{n+1} = [\rho]^{n} + \mathbf{F}_{\rho}(\mathbf{U}) \\
&[E]^{n+1} = [E]^{n} + \mathbf{F}_{E}(\mathbf{U})
\end{aligned} \tag{6}$$

The mass matrices $\mathbf{M}_S$ and $\mathbf{M}_F^{n+1}$, for structures and fluids respectively, are made diagonal by classical mass lumping techniques (see for instance [2]). The matrix $\mathbf{M}_F^{n+1}$ is variable with time for fluids due to the eulerian/ALE representation. The internal forces $\mathbf{F}_{\text{int}}$ result from the integration of the elementary structural stresses, whereas $\mathbf{F}_P$ result from the integration of the elementary pressure forces and $\mathbf{F}_{\text{trans}}$ are the nodal explicit transport forces for fluids.

The discrete kinematic constraints are expressed by means of a coupling matrix $\mathbf{C}^{n+1}$, acting on discrete velocities at next mid-step $n+3/2$ for structures and next step $n+2$ for fluids, and a right-hand side vector $\mathbf{S}^{n+1}$, both variable with time.

The system is completed by two finite volume equations, expressing the update of the density and the total energy within fluid cells using flux vectors $\mathbf{F}_{\rho}$ and $\mathbf{F}_E$ computed on the faces of the cells. This finite volume choice for the conservations of mass