Ocean Engineering 55 (2012) 219–234

Contents lists available at SciVerse ScienceDirect

Ocean Engineering

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

Parallel implementations of coupled formulations for the analysis of floating production systems, Part II: Domain decomposition strategies

Breno Pinheiro Jacob *, Luciano Donizetti Franco, Marcos Vinicius Rodrigues, Fabrício Nogueira Correa, Bruno Martins Jacovazzo

LAMCSO—Laboratory of Computer Methods and Offshore Systems, COPPE/UFRJ—Post-Graduate Institute of the Federal University of Rio de Janeiro, Civil Engineering Department, Centro de Tecnologia Bloco B sala B-101, Cidade Universitária, Ilha do Fundão, Caixa Postal 68.506, 21945-970 Rio de Janeiro, RJ, Brazil

ARTICLE INFO

Article history:
Received 19 January 2012
Accepted 24 June 2012
Editor-in-Chief: A.I. Incecik
Available online 22 August 2012

Keywords:
Floating production systems
Mooring systems
Risers
Nonlinear dynamics
Coupled analysis
Parallel implementations

ABSTRACT

This work presents the implementation, on computers with parallel architecture, of domain decomposition strategies for the coupled analysis of floating production systems (FPS). The strategies are associated to formulations for the coupling of the equations of motion of hull and lines, and to different algorithms for the solution of these equations.

The strategies are grouped as "external" and "internal". The former incorporates a "master-slave" scheme where the hull equations are solved in the "master" processor, and the equations of each line are solved in the "slave" processors. This scheme is associated to an external subcycling procedure, where the time step employed to integrate the hull equations is larger than the step for the lines.

In the "internal" partition strategies, the FE mesh of each line is partitioned amongst the processors. Different strategies are presented, including an internal subcycling procedure associated to an explicit algorithm, using distinct time steps to integrate the equations of each partition (according to its physical characteristics); and an implicit domain decomposition method where completely arbitrary mesh partitions may be defined.

Results of case studies are presented, to assess the performance of the parallel implementations described.

1. Introduction

The behavior of floating production systems (FPS) for oil production activities in deepwater scenarios is characterized by large displacements and severe nonlinear dynamic effects; therefore efficient numerical simulation tools are required for their analysis. Moreover, it has already been established that, in such scenarios, the consideration of the coupling between the hydrodynamic behavior of the hull and the structural/hydrodynamic behavior of the mooring lines and risers is mandatory (Astrup et al., 2001; Chaudhury, 2001; Finn et al., 2000; Heurtier et al., 2001; Kim et al., 2001, 2005; Ormberg and Larsen, 1998; Tahar and Kim, 2008; Wichers and Devlin, 2001; Yang and Kim, 2010).

Considering that the use of time-domain coupled analysis tools may lead to excessive computational costs, previous works have proposed more expeditious solution procedures involving reasonable approximations, including frequency-domain analysis methods (Garrett, 2005; Low and Grime, 2010), and combined or "hybrid" schemes where the low-frequency and wave-frequency components of the hull motions are solved separately in the time and frequency domain, respectively, and the lines are represented by a lumped-mass approach (Low and Langley, 2006, 2008; Low, 2008, 2011).

On the other hand, the authors have been directing research efforts to the development of innovative, Finite-Element based time-domain computational strategies with improved efficiency for the nonlinear dynamic analysis of offshore structures; see for instance (Benjamin et al., 1988; Jacob and Ebecken, 1992, 1993, 1994a, 1994b). Special attention has been dedicated to the development and implementation of formulations for the coupling of the equations of motion that represents the hull and the lines (Correa et al., 2002; Correa, 2003; Jacob and Masetti, 1998; Jacob, 2005; Rodrigues et al., 2007; Senra et al., 2002; Senra, 2004). In this context, this work and the companion paper (Jacob et al., in press) describe coupled formulations for the analysis of floating production systems, and present parallel implementations associated to these formulations. The goal is to obtain improved computational efficiency while maintaining high levels of accuracy, associated to the use of a full time-domain method

* Corresponding author. Tel./fax: +55 21 2562 7385.
E-mail addresses: breno@coc.ufrj.br (B.P. Jacob), ldf@lamcso.coppe.ufrj.br (L.D. Franco), mvr@lamcso.coppe.ufrj.br (M.V. Rodrigues), fabricio@lamcso.coppe.ufrj.br (F.N. Correa), bruno@lamcso.coppe.ufrj.br (B.M. Jacovazzo).

0029-8018/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.oceaneng.2012.06.018

and to a rigorous representation of the lines by finite element (FE) models.

The companion paper (Jacob et al., in press) describes in detail different coupling formulations, namely the "weak coupling" **WkC** and "strong coupling" **StC** schemes. The **WkC** formulation is focused on the equations of motion of the hull: the coupling between the hydrodynamic model of the hull and the hydrodynamic/structural model of the lines is performed by forces acting on the right-hand side of the hull equations. In the **StC** formulation, the FE meshes of all mooring lines and risers are assembled together, and the hull is considered as a "node" of this model.

This work presents different parallel implementations associated to these coupling formulations for the analysis of FPS, in order to obtain an innovative computational tool with improved efficiency, by taking advantage of clusters of PC computers (or PCs with multicore processors) that are commonly available nowadays. At this point, it could be recalled that the design practice of FPS requires the simulation of several loading cases for a given model, or even several realizations of the same loading condition when irregular sea states are considered. Thus, the most obvious application of a parallel computing environment would be simply to run each independent simulation on a separate processor. However, strictly speaking this is not "parallel computing" since it does not involve developing or adapting algorithms specifically to take advantage of such computing environments. More important, it does not eliminate the need, motivation or practicality of actually developing parallel algorithms and formulations; as will be seen later in this work, typical situations where the proposed parallel implementations would be useful may be, for instance, when the number of available processors is larger than the number of loading cases to be run, and/or when each node of the cluster is a multi-core computer. In this latter case, an efficient use of the parallel implementations would be to run each loading case on a node of the cluster; each run being parallelized/distributed amongst the cores of the node.

Regarding the lines, the parallel implementations described here can be grouped as "external" or "internal". "External" implementations comprise a "master-slave" scheme where the hull equations are solved in the "master" processor, and the whole set of equations of each line (or groups of lines) are solved in the "slave" processors. In this implementation there is no internal partition or decomposition of the FE mesh of any line.

The "internal" implementations formally employ mesh partitions or Domain Decomposition methods. Such methods were originally proposed for use in structural systems comprised by regions (or *domains*) with very different physical properties, such as in fluid-structure or soil-structure interaction problems (Hughes and Belytschko, 1983; Hughes, 1987). Several classes of techniques can be classified as domain decomposition methods, including the *subcycling* techniques that employ distinct time steps for each region, all solved with the same time integration operator: implicit or (more usually) explicit (Belytschko et al., 1979; Belytschko and Lu, 1993; Belytschko and Mullen, 1977; Daniel, 1997; Hughes and Belytschko, 1983; Neal and Belytschko, 1989; Smolinski, 1996).

Another class of domain decomposition methods are the Implicit-Explicit partition methods (Hughes et al., 1979; Hughes and Belytschko, 1983; Liu and Belytschko, 1982), where each region is integrated with a different operator. For instance, in applications to soil-structure interaction problems, these methods employ an explicit operator at the more flexible subdomain (i.e., the soil, where the critical time step Δt_{cr} required for a stable integration is relatively higher), and an implicit operator at the stiffer region (i.e., the structure, where Δt_{cr} would be too small and therefore implicit schemes are advantageous). The most efficient implementation for these methods involves an "element partition" (Hughes et al., 1979), where the mesh is divided in implicit or explicit elements. The coupling amongst the different operators occurs as a consequence of the assembly procedure for the global effective matrix.

Those previous works described sequential implementations of domain decomposition methods. More recently, parallel implementations for structural systems have been presented, including domain decomposition methods based only on implicit partitions—such as the *Group Implicit* (GI) and the *Iterative Group Implicit* (IGI) methods (Modak and Sotelino, 2000; Sotelino, 1994), following ideas originally presented by Ortiz and Nour-Omid (1986), Ortiz et al. (1988, 1989).

In the implementation of Domain Decomposition methods to the coupled analysis of FPS, comprising the "internal" parallel implementations that will be presented in this work, the FE mesh of one or more lines is partitioned amongst the processors, and different time integration operators and/or time steps may be used on each subdomain. A first implementation of an implicit domain decomposition method for coupled analysis of offshore FPS has been presented by the authors in Rodrigues et al. (2007); here other implementations will be presented, including an "internal" subcycling procedure associated to an explicit algorithm, where different time steps can be employed to integrate the equations of each partition of the FE mesh of a line.

In the remainder of this paper, Sections 2 and 3 summarizes the equations of motion of the hull and lines, respectively. Next, Section 4 briefly describes the **WkC** and **StC** formulations for the coupling of these equations. Then, Section 5 describes the "external" partition of the lines associated to an external subcycling procedure, where the time step employed to integrate the equations of the hull can be larger than the time step for the equations of the lines. The final sections present the "internal" implementations that employ domain decomposition methods: Section 6 describes an "internal" subcycling procedure associated to an explicit algorithm, and Section 7 presents an implicit domain decomposition method where completely arbitrary partitions of the mesh of the lines may be defined, leading to a better load balancing between processors. Section 8 comments on the association of the external and internal parallel implementations with the **StC** coupling formulation. Results of case studies are presented in Section 9, to assess the performance of the parallel implementations described in this paper.

2. Equations of motion of the hull

2.1. Formulation: Large amplitude, rigid body equations of motion

On the weak coupling formulation **WkC**, the rigid-body motions of the hull are represented by the following set of twelve first order differential equations, comprising the exact large amplitude equations of motion (Meirovitch, 1970; Paulling, 1992), where the unknown variables are $\mathbf{x}$, $\boldsymbol{\omega}$, $\mathbf{v}$ and $\boldsymbol{\theta}$, (respectively translational and angular components of position and velocities of the body as functions of time):

$$\frac{d\mathbf{v}}{dt} = \mathbf{M}^{-1}\mathbf{f}, \quad \frac{d\mathbf{x}}{dt} = \mathbf{v} \tag{1a}$$

$$\frac{d\boldsymbol{\omega}}{dt} = \mathbf{I}^{-1}[\mathbf{m} - \boldsymbol{\omega} \times (\mathbf{I}\boldsymbol{\omega})], \quad \frac{d\boldsymbol{\theta}}{dt} = \mathbf{B}^{-1}\boldsymbol{\omega} \tag{1b}$$

$\mathbf{M}$ and $\mathbf{I}$ are 3×3 matrices with, respectively the dry mass of the hull and the moments/products of inertia, and $\mathbf{B}$ is a rotation matrix with sines and cosines of the Euler angles. Vectors $\mathbf{f}$ and $\mathbf{m}$ contain, respectively external forces and moments due to the environmental loadings of wind, wave and current. The calculation