Proceedings of the First PhD Symposium on Sustainable Ultrascale Computing Systems (NESUS PhD 2016)
Timisoara, Romania

Jesus Carretero, Javier Garcia Blas
Dana Petcu
(Editors)

February 8-11, 2016

The analysis of parallel OpenFOAM solver for the heat transfer in electrical power cables

Andrej Bugajev, Raimondas Čiegis
Vilnius Gediminas Technical University, Sauletekio ave. 11, Vilnius
andrej.bugajev@vgtu.lt

Abstract

Here we present the part of results obtained in PhD thesis "The investigation of efficiency of physical phenomena modelling using differential equations on distributed systems" by Andrej Bugajev. This work is dedicated to development of mathematical modelling software. While applying a numerical method it is important to take into account the limited computer resources, the architecture of these resources and how do methods affect software robustness. Three main aspects of this investigation are that software implementation must be efficient, robust and be able to utilize specific hardware resources. The hardware specificity in this work is related to distributed computations. The investigation is done for FVM method usage to implement efficient calculations of a very specific heat transferring problem. That lets to create technological components that make a software implementation robust and efficient. OpenFOAM open source software is selected as a basis for implementation of calculations and a few algorithms to solve efficiency issues are proposed. The FVM parallel solver is implemented and analyzed, it is adapted to heterogeneous cluster Vilkas.

Keywords Finite Volume Method, OpenFOAM, parallel algorithms, domain decomposition, distributed computing, parallel computing

I. Motivation

This work is dedicated to proposal of technological solutions for developing design rules for power transmission lines and cables (1, [1]), which have to meet the latest power transmission network technical and economical requirements.

In order to do that it is necessary to develop specific software solutions. At present, sizes of the power lines are up to 60% bigger than is necessary in terms of transmitted power. However, as the new distributed generating capacities are installed e.g. large wind farms, bio-gas plants or waist-to-energy plants, the infrastructure of power grid must be re-designed or new optimization strategies for the available grid must be developed. Power cables for power distribution applications are still rated according to IEC 287 and IEC 853 standards, which use the Neher and McGrath meth-

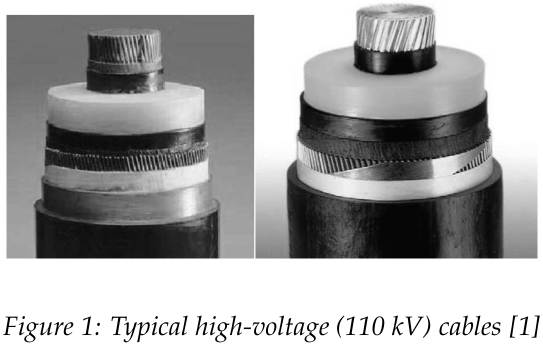

Figure 1: Typical high-voltage (110 kV) cables [1]

ods proposed in 1957 [2]. Obviously, these formulas cannot accurately account for the various conditions under which the cables are actually installed and used. They estimate the cable's current-carrying capacity (so-called *ampacity*) with significant margins to stay on the safe side [3]. The safety margins can be quite large and result in 50–70% usage of actual resources. A more accurate mathematical modelling is needed to meet the latest technical and economical requirements and to elaborate new, improved, cost-effective design rules and standards. Today there are many applications where analytical and heuristic formulas cannot describe precisely enough the conditions under which the cables are installed. The present standards require that the cable's current-carrying capacity must be reduced according to the worst-case scenario. To be on the safe side this rule is acceptable, but today the cost effective designing of cable installations comes first as the copper price level has reached its maximum value.

When we need to deal with mathematical models for the heat transfer in various media (metals, insulators, soil, water, air) and non-trivial geometries, only the means of parallel computing technologies can allow us to get results in an adequate time. To solve numerically selected models, we develop our numerical solvers using the OpenFOAM package.

II. Related work

The knowledge of dynamics (in time) of heat distribution in/around electrical cables is necessary to optimize the usage of electricity transferring infrastructure. It is important to determine: maximal electric current for the cable, optimal cable parameters in certain circumstances, cable life expectancy, other engineering factors. To solve the optimization problem it is necessary to implement an efficient modelling software for heat distribution in cables. Fundamentals of the heat distribution in cables are given in [4], but for further readings refer [5, 6, 7]. [8] and [9] presented efficient parallel numerical algorithms for simulation of temperature distribution in electrical cables for mobile devices and cars and solved inverse problem for fitting the diffusion coefficient of the air-isolation material mixture to the experimental data. Numerical algorithms for parabolic and elliptic problems with discontinuous coefficients have been widely investigated in many papers. The use of standard finite element method (FEM) to solve interface problems is equivalent to arithmetic averaging of discontinuous coefficients. The mixed FEM leads to the harmonic averaging if special quadrature formula are used – see, e.g. works by [10] and [5]. Conservative finite-difference schemes for approximation of parabolic and elliptic problems were derived by [11] and [12]. These schemes are robust and use only general assumptions on the position of the interface. Also such finite difference schemes were proposed, which approximate with the second order of accuracy both – the solution and the normal flux through the interface – see [13, 14] for details.

In recent years, scalability and performance of parallel OpenFOAM solvers are actively studied for various applications and HPC platforms. In [15] it is noted that the scalability of parallel OpenFOAM solvers is not very well understood for many applications when executed on massively parallel systems.

We note that an extensive experimental scalability analysis of selected OpenFOAM applications is one of the tasks solved in PRACE (Partnership for Advanced Computing in Europe) project, see [16], [17]. In [16] are presented results on IBM BlueGene/Q (Fermi) and Hewlett Packard C7000 (Lagrange) parallel supercomputers for a few CFD applications with different multiphysics models. The presented experimental results are showing a good scaling and efficiency with up to 2048–4096 cores. It is noted that such results are expected when balancing between computation, message passing and I/O work is good. Obviously, the next generation of ultrascale computing systems will cause additional challenges due to their complexity and heterogeneity.

The most important challenges for parallel solvers implemented in OpenFOAM are the following: a) efficiency of solvers on hybrid heterogeneous parallel systems, b) sensitivity of the parallel preconditioners to data distribution algorithms, c) workload balancing on heterogeneous parallel systems. For mathematical models describing coupled multi-physics problems, it is important to investigate two different approaches to design robust and efficient solvers for such problems [18]. Monolithic solvers operate directly on the system of nonlinear algebraic equations, obtained after the discretization ofthe system of PDEs. In the partitioning approache the discrete system is solved by using the single-physics solvers in decoupled fixed-point iterations. The latter aproach is implemented in OpenFOAM. A good review for a comparison of some popular fixed-point methods is given in [19].

III. Thesis idea

In this work, we study the performance of parallel OpenFOAM-based solver for heat conduction in electrical power cables. For computational experiments, we use the following 2D benchmark problem:

$$\begin{cases} c\rho\dfrac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + q, & t \in [0, t_{max}], x \in \Omega, \\ T(x,0) = T_b, & \text{when } x \in \Omega, \\ T(x,t) = T_b, & \text{when } x \in \partial\Omega, \\ [T] = 0, \quad [\lambda \nabla T] = 0 & \text{when } x \in \partial\Omega_D, \end{cases} \quad (1)$$

here $x = (x_1, x_2)$, $T(x,t)$ is temperature, $\lambda(x) > 0$ is heat conductivity coefficient, $q(x,t,T)$ is the source function, $\partial\Omega$ is the contour of domain Ω, $\rho(x) > 0$ defines mass density, $c(x) > 0$ is specific heat capacity, T_b, t_{max} are given constants. Operator $\nabla \cdot (\lambda \nabla T) = \sum_{j=1}^{2} \frac{\partial}{\partial x_j}\left(\lambda \frac{\partial T}{\partial x_j}\right)$ is the diffusion operator. The solution and flux continuity conditions are satisfied on boundaries of domains with different diffusion coefficients $\partial\Omega_D$.

When we need to deal with 2D and 3D mathematical models for the heat transfer in various media (metals, insulators, soil, water, air) and non-trivial geometries, only parallel computing technologies can allow us to get results in an adequate time. To solve numerically selected models, we develop our numerical solvers using the OpenFOAM package. OpenFOAM is a free, open source CFD software package. It has an extensive set of standard solvers for popular CFD applications. It also allows us to implement new models, numerical schemes and algorithms, utilizing the rich set of OpenFOAM capabilities. The important consequence of this software development approach is that numerical solvers can automatically exploit the basic parallel computing capabilities already available in the OpenFOAM package.

In this work, we study and analyze the parallel performance of OpenFOAM-based solver for heat conduction in electrical power cables. The main goal is to consider the scalability and efficiency of the developed parallel solver in the case when the parallel system is not big, but it consists of non homogeneous multicore nodes. The mesh is adaptive and it is partitioned by using Scotch method. Then load balancing techniques must be used in order to optimize the parallel efficiency of the solver. The second aim is to investigate the sensitivity of parallel preconditioners with respect to the number of processes.

IV. Conclusions and future work

1. Smaller problems enable a better caching and give a hardware-based speed-up for computations.
2. The uniform distribution of problems sizes is enough to solve the problem on homogeneous set of nodes, however this strategy is inefficient on heterogeneous set of nodes.
3. The load balancing lets to use different nodes efficiently in a heterogeneous cluser.
4. The future investigation of parallel efficiency dependence on preconditioners may lead to additional optimization of parallel solvers. This is especially important for large parallel systems.
5. One of the main challenges in future work is modelling the problem with multi-physics on parallel systems. In this case some parts of the whole domain have effects, described by Navier-Stokes equations and the rest part has diffusion only.

Acknowledgment

The paper was supported by NESUS project “Winter School & PhD Symposium 2016”.

References

[1] Z. Dongping. “Optimierung zwangsgekühlter Energiekabel durch dreidimensionale FEM-

Simulationen," *Doctoral thesis, Universität Duisburg-Essen*, 2009.

[2] J. H. Neher, M. H. McGrath. "The Calculation of the temperature rise and load capability of cable systems," *AIEE Transactions*, Vol. 76, Part III, pp. 752–772, 1957.

[3] I. Makhkamova. "Numerical Investigations of the Thermal State of Overhead Lines and Underground Cables in Distribution Networks," *Doctoral thesis, Durham University*, 2011.

[4] F. Incropera, P. DeWitt, P. David. *Introduction to heat transfer,* John Willey & Sons, New Yourk, 1985.

[5] A. Ilgevicius. "Analytical and numerical analysis and simulation of heat transfer in electrical conductors and fuses," *Doctoral thesis, Universität der Bundeswehr München*, 2004.

[6] A. Ilgevicius, H.D. Liess. "Calculation of the heat transfer in cylindrical wires and electrical fuses by implicit finite volume method," *Mathematical Modelling and Analysis*, Vol. 8, No. 3, pp. 217–228, 2003.

[7] J. Taler, P. Duda. *Solving Direct and Inverse Heat Conduction Problems,* Springer, Berlin, 2006.

[8] R. Čiegis, A. Ilgevičius, H. Liess, M. Meilūnas, O. Subač. "Numerical simulation of the heat conduction in electrical cables," *Mathematical modelling and analysis*, Vol. 12, No. 4, pp. 425–439, 2007.

[9] Raim. Čiegis, Rem. Čiegis, M. Meilūnas, G. Jankevičiūtė, V. Starikovičius "Parallel numerical algorithm for optimization of electrical cables," *Mathematical modelling and analysis*, Vol. 13, No.4, pp. 471–482, 2008.

[10] R. Falk, J. Osborn, "Remarks on mixed finite element methods for problems with rough coefficients," *Math. Comp.*, Vol. 62, No. 205, pp. 1–19, 1994.

[11] A.A. Samarskii, *The Theory of Difference Schemes*. Marcel Dekker, Inc., New York–Basel, 2001.

[12] A.N. Tichonov, A.A. Samarskii, "Homogeneous finite difference schemes," *Zh. Vychisl. Mat. Mat. Fiziki*, Vol. 1, No. 1, pp. 5–63, 1961.

[13] V.P. Il'in, "High order accurate finite volumes discretization for Poisson equation," *Siberian Math. J.*, Vol. 37, No.1, pp. 151–169, 1996.

[14] R. LeVeque, Z. Li. Erratum, "The immersed interface method for elliptic equations with discontinuous coefficients and singular sources," *SIAM J. Numer. Anal.*, Vol. 32, No 5, pp. 1704–1704, 1995.

[15] O. Rivera, K. Furlinger, D. Kranzimuller, "Investigating the scalability of OpenFOAM for the solution of transport equations and large eddy simulations," *Lecture Notes in Computer Science*, Vol. 7017, pp. 121–130, 2011

[16] P. Dagna. "OpenFOAM on BG/Q porting and performance," *Prace report*, CINECA, Bologna, Italy 2012.

[17] M. Culpo. "Current bottlenecks in the scalability of OpenFOAM on massively parallel clusters," *Prace white papers*, CINECA, Bologna, Italy 2012.

[18] R. Muddle, M. Milhajlovic, M. Heil. "An efficient preconditioner for monolithically-coupled large-displacement fluid-structure interaction problems with pseudo-solid mesh updates," *Journal of Computational Physics*, Vol. 231, No. 21, pp. 7315–7334, 2012.

[19] U. Kuettler, W. Wall. "Fixed-point fluid-structure interaction solvers with dynamic relaxation," *Computational Mechanics*, Vol. 43, No. 1, pp. 61–72, 2008.