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Progress on the Multiphysics Capabilities of the Parallel Electromagnetic ACE3P Simulation Suite

Oleksiy Kononenko, Lixin Ge, Kwok Ko, Zenghai Li, Cho-Kuen Ng, and Liling Xiao

SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA
Oleksiy.Kononenko@slac.stanford.edu

Abstract — ACE3P is a 3D parallel simulation suite that is being developed at SLAC National Accelerator Laboratory. Effectively utilizing supercomputer resources, ACE3P has become a key tool for the coupled electromagnetic, thermal and mechanical research and design of particle accelerators. Based on the existing finite-element infrastructure, a massively parallel eigensolver is developed for modal analysis of mechanical structures. It complements a set of the multi-physics tools in ACE3P and, in particular, can be used for the comprehensive study of microphonics in accelerating cavities ensuring the operational reliability of a particle accelerator.

Index Terms - Eigenmode solver, Multi-Physics, particle accelerators.

I. INTRODUCTION

In a wide range of scientific and engineering applications, mechanical structures are a subject to external loading. This loading is often a source of vibrations that could pose serious problems to a structure leading to performance degradation or even damage. In accelerator modules the vibrations often cause microphonics, undesired electrical signals. Unless carefully studied and controlled, the microphonics may significantly affect the operational reliability of superconducting accelerating cavities having a narrow RF bandwidth. To analyze this adverse effect, mechanical and coupled electromagnetic analyses must be performed. For the large-scale or high-accuracy sensitive simulations it is advantageous to use parallel computing which can significantly reduce the simulation time.

For this purpose, ACE3P [1], a 3D massively parallel electromagnetic simulation suite, developed at SLAC National Accelerator Laboratory for the last decades will be enhanced to mechanical studies. Recently, within the existing framework, a new mechanical eigensolver for a modal analysis of accelerator components is implemented. Coupled with the powerful electromagnetic ACE3P modules, this solver provides an additional parallel multi-physics modeling capability for studying microphonics in the accelerator components.

II. MATHEMATICAL MODEL AND SOFTWARE DESIGN

In isotropic 3D domain Ω, we consider a governing equation of the linear elasticity to determine mechanical eigenmodes and frequencies [2]:

$$\nabla \bullet \sigma = -\omega^2 \rho u \,, \qquad (1)$$

where σ is the stress, ω is the angular frequency, ρ is the material density and u is the displacement field. On $\partial\Omega$ either the homogeneous Dirichlet or Neumann boundary conditions are considered:

$$u = 0 \,, \qquad (2)$$

$$\sigma \bullet n = 0 \,. \qquad (3)$$

Following the standard finite-element approach [2] the boundary value problem (1-3) is reduced to the weak integral form in Ω:

$$\int_\Omega (2\mu \frac{1}{2}(\nabla u + \nabla u^T) + \lambda(\nabla \bullet u)I) \bullet \nabla v d\Omega = \omega^2 \int_\Omega \rho(u \bullet v) d\Omega \,,$$

where v is a test function, λ and μ are the Lam*é* coefficients, respectively. Using the nodal higher-order basis functions and the 3D Gaussian quadratures the corresponding linear algebraic system is derived:

$$Ku = \omega^2 Mu \,,$$

where K and M are the stiffness and mass matrices respectively.

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Based on this model a new mechanical eigensolver is developed within the C++/MPI finite-element framework of the ACE3P simulation suite. This solver adds a new modelling capability in ACE3P's multi-physics module TEM3P, which is designed for integrated electromagnetic, thermal and mechanical analysis of accelerator components.

The simulation workflow consists of three main steps: pre-processing, executing the ACE3P module, and post-processing. While the pre-processing and post-processing are performed on the desktops, the ACE3P execution is carried out remotely on the supercomputers at the National Energy Research Scientific Computing Center [3].

The developed eigensolver has been extensively benchmarked showing an excellent agreement with the analytical models and other software, featuring a good performance and scalability.

III. MULTIPHYSICS ANALYSIS

Illustrating the multiphysics ACE3P features, we consider the TESLA superconducting cavity situated in a helium tank [4], see Fig. 1 for details.

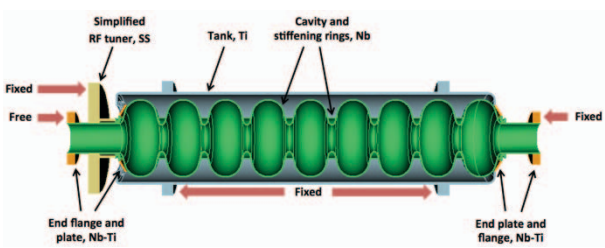

Fig. 1. The TESLA superconducting cavity in a cryogenic tank; the total structure length is 1.28 m.

The first five mechanical eigenmodes, see the second column in Table 1, have been calculated in 37 seconds on the 1.2M computational mesh utilizing 240 cores of NERSC Hopper system [3].

Table 1: Mechanical eigen frequencies of the TESLA cavity and the corresponding RF detuning

Mode	Frequency [Hz]	RF Detuning [Hz/μm]
1	74.18	0.060
2	160.92	0.039
3	220.12	-2.27
4	265.04	0.067
5	306.21	0.197

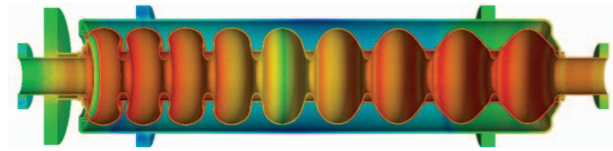

Fig. 2. Von Mises stress [a.u.] for the third mode.

To illustrate the postprocessing ACE3P capabilities, in Fig. 2 Von Mises stress is plotted for the third eigenmode on top of the deformed geometry.

The deformed vacuum models are used to calculate the RF frequency shift [5] for small deformations, see the third column in Table 1.

The deformations caused by the radiation pressure or by the low-frequency oscillations of the environment may be projected on the set of the orthogonal eigenmodes and the projection coefficients can later be used as the input for the low-level RF feedback system ensuring for operational reliability of the accelerating structure.

IV. CONCLUSION

A new parallel mechanical eigensolver is developed as a part of the ACE3P suite. It complements a set of the high performance electromagnetic simulation tools and, as illustrated, crucial in the multiphysics analysis of the large-scale problems in accelerator science.

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