COUPLED ANALYSIS OF ELECTROMAGNETIC, THERMO-MECHANICAL EFFECTS ON RF ACCELERATING STRUCTURES

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Abstract

One of the main problems to the designer of RF structures used in particle accelerators is to estimate their sensitivity to thermo-mechanical effects. These parameters are the basis for the choice of the tuning strategy and for the determination of the feedback architecture. We explored the possibility of using ANSYS®[1] to perform such simulations in a single environment. Some examples of the most common problems of interaction between electromagnetic fields and thermo-mechanical effects are presented and, when possible, compared to measurements. Problems encountered are outlined.

1 INTRODUCTION

As performances of RF structures for particle accelerators are pushed, the requirements for their thermo-mechanical properties become more and more stringent. Methods to foresee any interaction between electromagnetic fields and the thermo-mechanical structure have to be refined to give a precise input for the choice of the tuning strategy, to decide on the feedback architecture and performance, to evaluate the stability of the overall system.

Up to now electromagnetic simulators had only a simple interface to provide information to thermo-mechanical simulation packages. Some of them allow inserting the geometry of the structure to simulate in a standard CAD format. Even with these features, the exchange of information from one domain to the other (field distribution, temperature distribution, deformation etc.) is generally a tedious and time consuming process, and obliges to develop complicated routines to translate this information from one software to the other.

ANSYS® is the first multi-physics environment (to our knowledge) to include a High Frequency solver module, and we used it to perform coupled analysis of several RF structures. The exchange of information between one module and the other (RF ⇔ Mechanical ⇔ Thermal) is a built-in feature of the package that speeds up the simulations and reduces the risk of errors.

The High frequency module was introduced with version 5.4 of ANSYS® and was not free of bugs. Most of them have been corrected meanwhile, thanks to a good interaction we had with ANSYS® technical support, but some others still remain and will be outlined in this note. Several examples of the most common problems of interaction between RF fields and mechanics will be presented

2 COUPLED ANALYSIS WITH ANSYS®

In the design of RF structures, three physics domains have generally to be dealt with:

- Electromagnetism, ruled by the Maxwell equations
- Mechanics, ruled by Hooke's equations
- Thermodynamics, ruled by the equations of thermodynamics

In ANSYS® each set of equations can be solved by separate "modules" sharing the same geometry and the results of one module may be used as load cases to the others.

The High Frequency module has for the moment the limitation that only 3D elements can be used, so 3D simulations have to be performed also for virtually 2D problems (e.g. axis-symmetric structures where the modes of interest are also symmetric around the geometric axis).

On the other hand it has a powerful automatic meshing tool, where meshing precision can be specified for each different region of the problem geometry, thus allowing, in a simple way, an accurate meshing of complicate structures.

The solvers are based on the Finite Element Method (FEM) and do not require special computers to run properly. The examples shown in the following have been produced on a standard PC with reasonable solving times (max 1 hour). Basically the requirements for hardware are: as much memory (640 Mbytes at least) and space on the hard disk (at least 4GB) as possible.

Coupled analysis means using the results of the simulations in one domain as an input for the other domain. In a very general way the process can be described by the loop of fig. 1. Other logical paths are of course possible among the three simulations blocks, as we will see in the following examples.

3 EXAMPLES

3.1 Detuning of BOC cavity during operation.

The cavity used for the example is the 3 GHz Barrel-Open Cavity (BOC) proposed by I. Syratchev and R. Bossart for pulse compression of the CTF3 drive beam Klystrons. The resonant mode used for pulse compression is the $E_{10,1,1}$ to achieve a high Q factor (~180000).
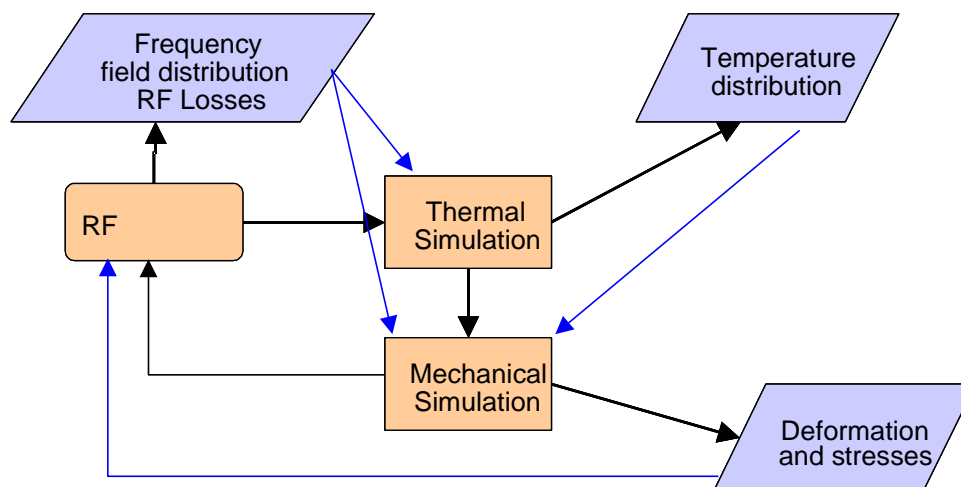
Fig. 1: Interdependency among the different modules and their outputs

The mechanical structure of the cavity is shown in figure 2, it consists in two 8 mm spinned and machined shells welded together by an electron beam. On each cell, 2 channels are installed to provide the necessary cooling. During operation, the cavity has to dissipate 15.5 MW of peak RF power (average value is 1.75 KW). The geometrical and RF operational symmetries allow performing the simulation only with a fortieth of the cavity, reducing the problem size considerably. Fig. 2 shows the two contiguous domains implemented by the mesh tool: in cyan the RF domain and in magenta the mechanical/thermal domain
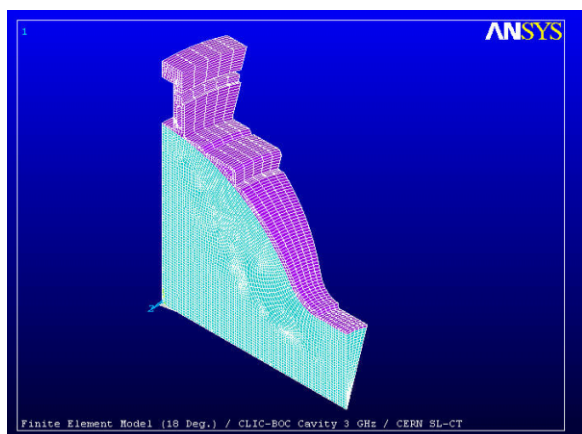

Fig. 2: The RF and mechanical domains.

The frequency of the cavity during operation will be controlled through the temperature of the cooling water. Therefore we performed extensive simulations to determine the detuning during power up and the range of tuning with 10ºC change. The procedure used for the power–up detuning is the following:

- Compute the steady state frequency by using the RF domain.
- Compute the initial (no RF) steady state temperature distribution using the thermal domain. Forced convection in the cooling channels and natural convection into the surrounding air (303K) have to be applied as boundary conditions.
- Thermal transient run by applying heat flux distribution from step 1, scaled using the nominal pulse shape (length 4 µs, rep. rate 25Hz, 40 MW from the source). From t=0 to t=39.990ms heat flux is 0, at t=39.996ms heat flux is maximum and at t=40.000ms heat flux is 0.
- Calculate the mechanical deformations by using the temperature distribution from step 3. The atmospheric pressure has also to be applied as input load. The structural model is used.
- Update the nodes' position.
- Calculation of the resonant frequency of the deformed cavity, deformation from step 4 is used

The calculated frequency shift (at steady state) is +110 KHz and the maximum temperature offset is +4.2 K. These values are in perfect agreement with the experience.

The detuning due to a cooling water temperature change can be evaluated with a very similar procedure. The result is ±210 kHz for a temperature change of ±5K. This is also in perfect agreement with practical experience.

3.2 Lorentz force detuning of a superconducting cavity

Another typical problem that has to be studied in a multiphysics environment is the calculation of the detuning due to the so-called Lorentz forces experienced by elliptical superconducting cavities under pulsed conditions. It can be shown, in fact, that electromagnetic fields exert a pressure on the cavity walls that deform the cavity itself. The detuning caused by this deformation can be of the order of the bandwidth of the system or even more, so that, it is no more possible to correctly fill the

cavity with electromagnetic energy at the desired frequency.

The amplitude of the deformation can easily be calculated using a procedure similar to what has been done for the other cases:

- evaluate the electromagnetic field distribution of the accelerating resonant mode using the RF domain.
- calculate the Lorentz forces using the formula:

$$\left(\vec{\mathbf{F}} \cdot \mathbf{d}\vec{\mathbf{S}}\right)\vec{\mathbf{n}} = \left[\frac{1}{4}\left(\mu \left|\vec{\mathbf{H}}\right|^2 - \varepsilon \left|\vec{\mathbf{E}}\right|^2 \right) dS \right] \vec{\mathbf{n}} \qquad (1)$$

where $\vec{\mathbf{F}}$ is the Lorentz force, $\mathbf{d}\vec{\mathbf{S}} = dS\,\vec{\mathbf{n}}$ is an oriented surface element on the cavity walls, with normal unitary vector $\vec{\mathbf{n}}$ oriented towards the outside of the cavity.

- calculate the mechanical deformation due to elementary Lorentz forces using the mechanical domain.
- Calculate the resonant frequency of the deformed cavity, deformation from step 3 are used.

Coupled field simulations have been applied to a four cell, β=0.7, 352 MHz cavity for which experimental measurement are available. Calculations have been conducted taking into account different ideal boundary conditions, respectively cavity blocked at both ends and cavity blocked at one end and free at the other one. The measured detuning value lies between these two numerical results. Forthcoming detailed simulations, taking into account the stiffness of the support frame, are underway.

The measured detuning value, at 2K and under atmospheric pressure, is –7.77 Hz/(MV/m)^2.

Numerical results are respectively –3.5 Hz/(MV/m)^2 for all blocked boundary condition (Fig. 3) and –26.0 Hz/(MV/m)^2 for blocked-free boundary condition.
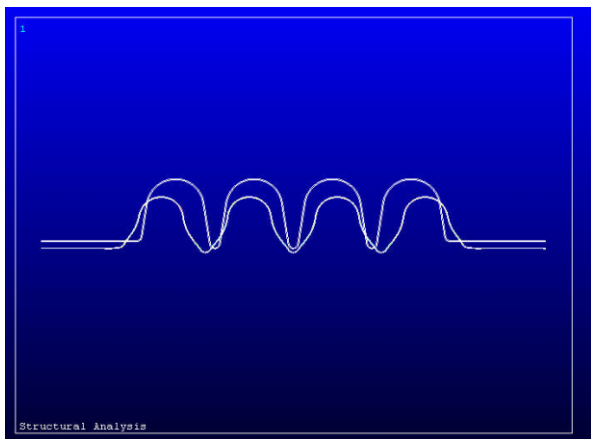

Fig. 3: Deformation due to Lorentz Forces (amplified)

4 CONCLUSIONS

We explored the possibilities of ANSYS® to perform multiphysics simulations in a single environment. As shown in the preceding examples this attempt was successful and opens the way to a more systematic approach to RF cavity design, where Mechanical and RF aspects can be studied at once. This can be done of course even with other software packages, but the exchange of information between Electromagnetic field simulators and Structural/thermal simulators can be difficult and can lead to errors. With ANSYS® the exchange of information between the different modules is a built-in feature of the software, and the designer can focus on the physics of the problem more than on the simulation.

It's not a long time since ANSYS® has this feature, so some bugs were found during the study. The vendor solved some of them on our request, the main bug remaining are in the built-in energy and power calculation macros. In fact they do not take into account the harmonic nature of RF power dissipation and Energy stored when simulating in the frequency domain, therefore a factor 2 has been omitted. We developed our own macros to evaluate power, energy and Lorentz forces.

Other macros can easily be developed to calculate all the RF parameters of a cavity, like the Q factor, Shunt impedance etc.

According to our experience, absolute frequencies evaluated by ANSYS® can differ from theoretical even more than 1%, probably due to the use of 3D elements (unless very precise meshing is arranged leading generally to very big scratch files and very long computing time). On the other hand, detunings are generally evaluated with an astonishing precision, due to the fact that the displacements of nodes are computed very precisely, while the error in their absolute position is the same before and after displacement. Therefore the procedures applied above are very useful during mechanical design, to asses the influence of external (or internal) perturbations on the mechanical structure of the RF cavity.

5 ACKNOWLEDGMENTS

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6 REFERENCES

[1] http://www.ansys.com/
[2] Syratchev, I., RF pulse compression for the drive beam accelerator, in Away-Day: a Review of the Preparation of the CTF3 Design , 6 Nov 1998 , Ferney-Voltaire, France. - CERN-OPEN-98-034 ; CLIC-Note-383.