COMPUTER CODES FOR RF CAVITY DESIGN*

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Abstract

In RF cavity design, numerical modeling is assuming an increasingly important role with the help of sophisticated computer codes and powerful yet affordable computers. A description of the cavity codes in use in the accelerator community has been given previously. The present paper will address the latest developments and discuss their applications to cavity tuning and matching problems.

Introduction

Over forty papers presented at LINAC'90 involved some level of simulation effort in a cavity design. This suggests that numerical modeling, at least of RF cavities, has gained wide acceptance in the accelerator community. The same is also true in the microwave tube industry where R & D work on cavity design relies heavily on computer simulations. One outstanding contributing factor to this development is the availability of increasingly sophisticated computer codes, particularly those that model in three dimensions. Many accelerator components are inherently three-dimensional (3D) such as the input coupler cavity in a linac. Another factor can be attributed to the advent of powerful yet affordable computers with sufficient memory and a fast enough processor to make feasible the simulations of realistic structures. Specifically, we refer to the engineering workstations that have become competitive and even superior to supercomputers in cost and performance. Although the present paper is primarily concerned with computer codes, the importance of this new computing environment should not be overlooked as it holds the promise to realize numerical modeling as a viable computer-aided-design tool for RF cavity engineering.

A description of the cavity design codes in use in the accelerator community can be found in the compendium put forth by the Los Alamos Accelerator Code Group (LAACG) [1] and will not be repeated here. A summary of field and particle solvers has also been given previously [2]. This paper will instead focus on the latest developements in 3D electromagnetic codes (no beam effects) that are relevant to RF cavity design. We will demonstrate their applications with practical examples from various research projects at SLAC. These include the design of periodic structures, waveguide-loaded cavities and travelling wave components. The paper will begin with some comments on computer-aided-design, to be followed by brief discussions on finite difference versus finite element codes and on frequency-domain versus time-domain simulations. After the presentation of the numerical results, we will conclude with several final remarks on the future direction of RF cavity modeling.

* Work supported by Department of Energy, contract DE-AC03-76SF00515.

Computer-aided-design (CAD)

CAD is already firmly established in many engineering disciplines and its advantages are well recognized. Among them are shorter design cycles and higher first-time success rate. For RF cavity designers, CAD has been in existence for over twenty years in codes like LALA and TWAP which model cylindrically symmetric structures. Since then they have been superseded by other two-dimensional (2D) codes, most notably SUPERFISH and URMEL. These programs have through the years, saved the cavity designers a considerable amount of time and effort in actual modeling and cold-tests. Using these codes, one can optimize a cavity's parameters to design specifications and learn about properties of the cavity which otherwise would have been difficult to determine experimentally (e.g. the peak fields on the cavity walls).

While the usefulness of 2D codes is indisputable, accelerators and power sources are comprised of many non-symmetric structures that require 3D modeling. The input coupler cavity in a linac has been mentioned as an example. Another is the output cavity of a klystron. These critical components are responsible for power input/output therefore their specifications have to be optimized for performance. At the same time one has to ensure that instabilities, beam or RF related, have been avoided. In the absence of a design tool, the engineering of these cavities could understandably be time consuming and costly as many design requirements have to be met. But that situation is changing as 3D codes are beginning to make an impact on the design process.

The significant task of developing a 3D CAD program requires substantial human resources and expertise and has been the main thrust of several code groups in the past decade. The MAFIA and ARGUS codes are examples of such multi-year team efforts, and there are others. Even though developmental work on most of these codes is still continuing, many complex cavities and structures can already be evaluated and analyzed using the capabilities presently available. This is an important step because it has become apparent that 3D codes are needed to help meet the design challenge posed by the next generation of accelerators and the power sources that drive them. These systems demand higher performance and tighter tolerance from RF cavities and structures than do previously. This paper will later show that the two cavities mentioned earlier can be modeled realistically to yield results that compare very well with measurements. These plus similar successful experiences elsewhere have added to our optimism that CAD for RF cavities of arbtirary geometry is indeed feasible with the present state of the art computer software and hardware.

Finite Difference versus Finite Element

RF cavity codes are generally of two types: finite difference (FD) and finite element (FE). While a lengthy discussion on the two methods is beyond the scope of the paper, some important differences are worth pointing out. The foremost of them is the mesh. For simplicity of illustration, we show in Fig. 1 the 2D geometry for a single cell of a SLAC-type accelerator structure as modeled by a FD code (URMEL) and a FE code (YAP) [3]. Using about the same number of nodes YAP approximates the disk shape more closely with an irregular mesh than URMEL does with a regular mesh. This improvement is expected to be more dramatic in 3D geometries and it is particularly relevant when one considers tuning cavities of complex shapes to high precision. We are planning to compare the two types of codes in this respect in the near future. Nelson has already performed similar analysis on 2D codes and he found better accuracies with his FE code YAP. FE codes, however, can have drawbacks of practical concern. Unless the mesh generation is automated the geometry could be tedious to set up, and depending on whether the code deals with fields or potentials, the boundary conditions could be nontrivial to apply. On the contrary these procedures are quite straightforward for FD codes.

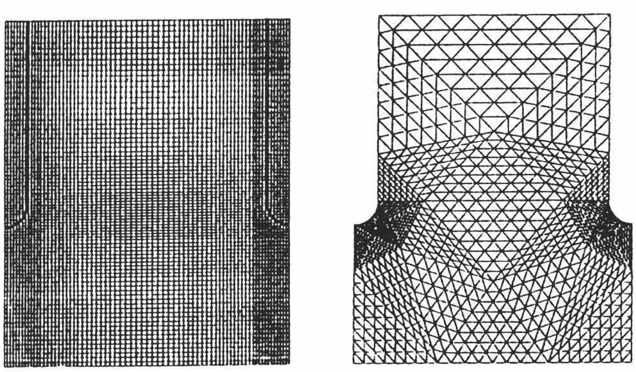

Fig. 1 Disk-loaded Waveguide as modeled by URMEL and YAP.

From the mechanical engineering standpoint, there is an additional advantage FE cavity codes have over FD ones in that most mechanical design codes work with finite elements. Therefore one can conceivably calculate the power loss densities with a FE cavity code and use the data directly in a thermal code for heat stress analysis, all on the same mesh. Otherwise one needs to interpolate the data from a FD mesh to a FE mesh which our experience has shown to be a laborious exercise, and could lead to inaccurate results. For this reason and the one described above in regard to geometry modeling, there is a growing interest in FE cavity codes despite the steeper learning curve one might encounter in using them.

Frequency Domain versus Time Domain

The properties of RF cavities can be studied numerically either in the frequency domain or time domain. For normal mode calculations, the frequency domain is the method of choice. One solves the time-harmonic Maxwell's equations as an eigenvalue problem by imposing the appropiate boundary conditions and obtains the mode frequencies and mode patterns as eigenvalues and eigenfunctions. Efficient solvers have been written specifically to give fast, direct solutions. With some, such as the Semi-Analytic Processor (SAP) [4], many modes can be obtained in a single run. The SAP is implemented both in MAFIA and ARGUS. Through post-processing, circuit parameters such as the quality factor and shunt impedance can be evaluated. Almost all the solvers deal with real eigenvalues so only high Q modes like standing wave solutions in non-periodic structures or travelling wave solutions in periodic ones can be found. The latter is possible through the application of the quasi-periodic boundary condition which we will discuss more later. Low Q modes with complex frequencies such as those that are not trapped in waveguide-loaded cavities, cannot be treated by these solvers. We will show in a later section how this difficulty can be overcome with theoretical methods. The EMAS code can handle lossy material in the frequency domain but our experience with it has been limited.

Travelling waves in arbitrary structures can be modeled in the time domain where Maxwell's equations are solved as an initial value problem. By way of the waveguide-port boundary conditions power can be injected into a structure and extracted from it as if it were matched, all at a single frequency. Two effects can be obtained from this approach; the transient during the initial filling and the scattering due to the structure at steady state. The latter is of interest for matching purposes as it allows the S parameters for the structure to be determined.

A word of caution needs to be raised regarding using either approach with FD codes. Ideally, one wishes to mesh as closely to the cavity shape as possible. However, what is ideal for the geometry might not necessarily be good for the solver. In the frequency domain, the width of the frequency spectrum increases inversely with the the smallest mesh size. If the spectrum becomes too wide so that the wanted modes constitute only a small fraction of it, then the solver will have a difficult time in discriminating them from the unwanted ones. Of course one can solve for more modes but that would mean more CPU time which could be substantial in large problems. In the time domain, the smallest mesh size also determines the time step for integration through the Courant condition. An overly fine mesh may lead to such a small time step that the run may become prohibitively expensive. Hence, the prudent strategy is to first consider the given computing resources, then configure the mesh with the solver in mind so that the solutions can be obtained in an expeditious manner.

3D Cavity Codes

There are six 3D codes we are aware of that have been in active use for RF cavity and component design: MAFIA, ARGUS, SOS, CAV3D, EMAS and HFSS. Except for EMAS and HFSS which are FE codes, the rest are all FD codes. The first three 3D codes (MAFIA, ARGUS, SOS) have both time and frequency domain solvers so they are fairly similar as far as cavity modeling goes. MAFIA does have the capability to model curvature with triangular cells which is a distinct advantage. EMAS is another multi-purpose code in that it evaluates in time and frequency domain also. On the other hand CAV3D is strictly an eigenvalue solver while HFSS only calculates S parameters at a prescribed frequency.

Up until recently 3D cavity codes have been mostly run by experts on mainframe computers. Since the arrival of the workstation, we do not expect that trend to continue. Our experience with such a machine is that it is quite capable of performing the large simulations that are necessary for realistic cavity design. In fact the actual clocktime for job turnaround can often be much shorter than that obtainable from a supercomputer even though the latter has the faster processor. This is due to the fact that the supercomputer is shared by many users while a workstation can dedicate its CPU entirely to one. The IBM RS6000 Model 560 or the HP 7000 Model 950 can deliver a nontrivial fraction of the performance of a Cray YMP which is quite remarkable considering their cost ratios. The system specifications that allow these high-end workstations to accomplish such a feat include more than 128 Mb of memory and over 25 MFLOPS in CPU power. Our experience shows that ten modes can be found by MAFIA on one of these machines in less than seven hours, simulating close to half a million mesh points. The gain in turnaround time factors heavily in a design process when many runs may be required. Thus these computers could be the vehicle that brings 3D modeling of complex structures much closer to being practical for the cavity designer.

Most of the codes listed here have been ported to this new platform not only because of the hardware performance but also because of the powerful graphical interface. Visualization is an extremely important aspect of 3D modeling as it is used in geometry setup and in post-processing. These two steps constitute the bulk of the modeling effort. In addition, code developers increasingly are recognizing the need for user friendliness. As a result the use of 3D codes will not be left to the experts, but rather a novice user can get started and learn to run them effectively in a reasonably short time frame. MAFIA 3.1 represents a marked change in that direction and the code has justifiably been well received.

Latest in 3D Cavity Modeling

The two codes we have most experience with are MAFIA and ARGUS. Therefore the examples given below have been drawn from simulations we have done with them. Presently we have access to SOS, EMAS and HFSS as well so that perhaps in the future we would be able to provide a comparison between these codes in terms of usage, accuracy and so forth. In the following we will describe the latest developements in 3D cavity modeling and will show numerical results obtained from their applications.

(a) Quaisi-Periodic Boundary Conditions

The quasi-periodic boundary conditions permit arbitrary phase advance to be specified across one cell of a uniform periodic structure. The benefits are threefold. First, it allows the dispersion diagram to be generated with a single mesh. Second, better geometry resolution is now possible since the whole mesh can be used to model just one cell. Third, because the field solutions are travelling wave modes, one can calculate the group velocity via the Poynting flux and stored energy. This implementation is available in both MAFIA 3.1 and ARGUS 24.

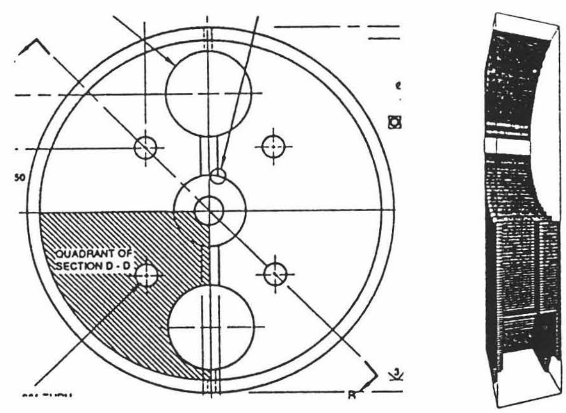

Fig. 2 MAFIA Model of X-Band SLAC Cell with Pumping Slot.

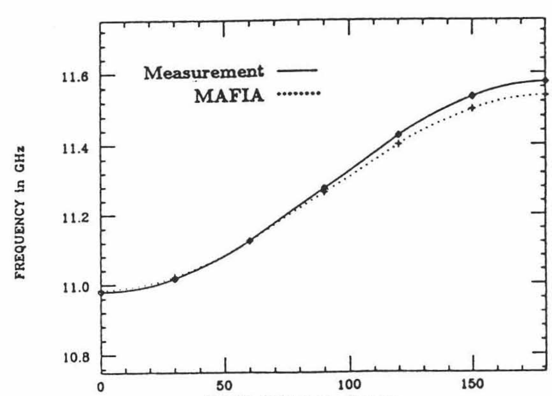

Fig. 3 Dispersion Diagram.

Fig. 2 shows a MAFIA example of an X-Band SLAC accelerator cell coupled to the vacuum manifold through rectangular pumping slots. Fig. 3 is the MAFIA result for the dispersion diagram as compared with measurements. The maximum discrepancy is about 20 MHz. Admittedly the agreement might have been better had a finer mesh been used; here it suffices to illustrate the usefulness of the capability. In modeling high Q cavities with FD codes, the results are often mesh sensitive. This is an area where FE codes may be advantageous when precise cavity dimensions to the order of the machining tolerance are to be expected.

(b) Loaded Q Determination

Waveguide-loaded cavities are employed among other uses, to damp higher-order modes (HOM) in accelerators and to extract power from the beam in klystrons. In HOM damping scheme the idea is to couple out all but the accelerating mode. In a klystron output cavity trapped modes are undesirable so all modes are coupled out. The figure of merit for the external coupling is the loaded Q and good damping requires that the loaded Q be low. As pointed out earlier, low Q modes cannot be modeled correctly by most frequency domain solvers because they calculate real eigenvalues in a closed cavity. Nevertheless, the theoretical method of Kroll-Yu [5] overcomes this difficulty by using the closed cavity data for various waveguide lengths to evaluate the complex frequencies and thus the loaded Q. We should also mention that Arcioni has developed a theory which he incorporated into the POPBCI code [6] and it can generate an impedance spectrum for the matched cavity from the same numerical data that the Kroll-Yu method uses. From the widths of the resonances one can determine the loaded Q approximately.

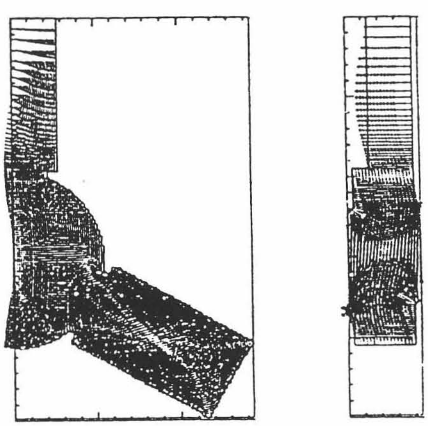

Fig. 5 ARGUS Solutions for the Magnetic and Electric Field of Dipole Mode in X-Band Damped Cavity.

Figure 5 shows the ARGUS field solutions for the dipole mode in a 3-waveguide damped cavity at X-Band. Because the waveguide ends are shorted, these are not the true solutions for the mode when the waveguides are matched. Still the field distribution already gives an indication that the coupling to the waveguides is strong. By applying the Kroll-Yu method to this and other data, we found a loaded Q of 30.

We next show an X-Band 3-gap klystron output circuit as another example of a waveguide-loaded cavity. For this cavity there is measured data to compare with the ARGUS/Kroll-Yu calcalutions and as Fig. 7 indicates, they agree remarkably well with each other.

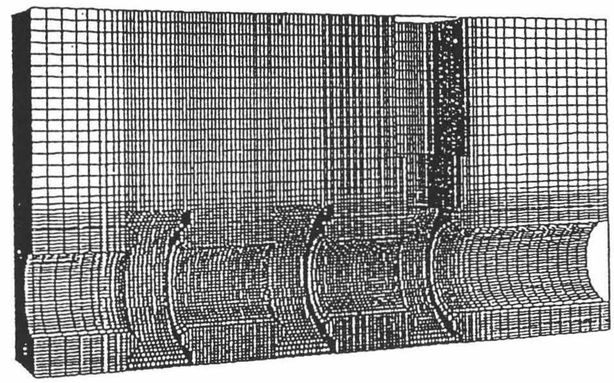

Fig. 6 ARGUS Model of X-Band 3-Gap Klystron Output Circuit.

Freq. in GHz (Q_L)	π	$2\pi/3$	2π
Measured	10.07 (47)	10.40 (45)	11.54 (19)
Calculated	10.05 (45)	10.33 (44)	11.53 (20)

Fig. 7 Comparison of ARGUS/Kroll-Yu Results with Experiment.

(c) S Parameters Calculation

Travelling wave structures and components are common in accelerator and RF power systems. They are responsible for power transport and the determination of their scattering properties or S parameters is essential for their design. S parameters are calculated by MAFIA in the time domain. The waveguide-port boundary condition enables power to be launched as an incoming wave at a selected frequency while it also allows any reflected wave to be totally outgoing at the same frequency. These ports are used to terminate the waveguides that are connected to the structure of interest. The code follows the evolution of the injected power in time until the fields inside the structure has reached steady state. The complex amplitude of the reflected wave at the input port and that of the transmitted wave at the output port are monitored in time. At steady state the time average over many cycles of these quantities, properly normalized to the input amplitude, yield the S parameters. Since the boundary conditions are set up for a single frequency, the incoming wave should be launched smoothly to make sure that few other frequencies are excited.

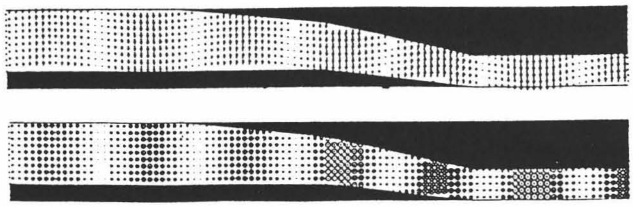

Fig. 8 Electric and Magnetic Fields of Travelling Wave at Steady State in X-Band Transducer.

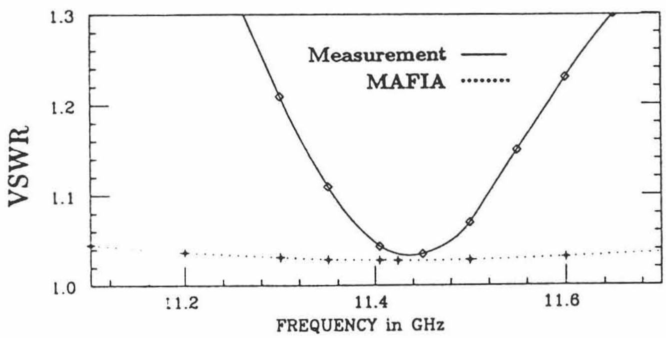

Fig. 9 MAFIA comparison with Measurements.

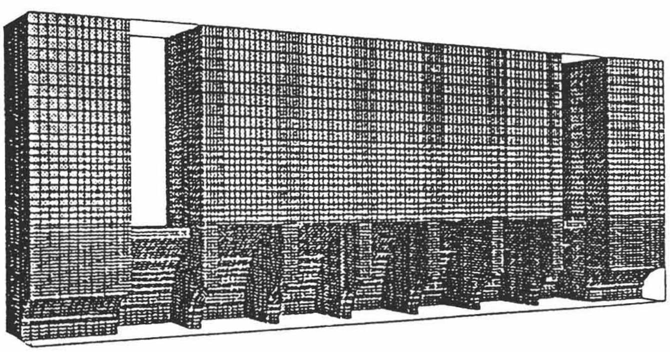

Fig. 10 MAFIA Model of 7-Cell X-Band Accelerator Section with Input/Output Couplers.

Fig. 8 shows the MAFIA calculations for an X-Band Transducer. These are the travelling wave fields at steady state and the propagation is from right to left. The waveguide-port boundary conditions are applied at the terminating planes at either end. From the S parameters, one can find the VSWR for the structure. The VSWR comparison with measurements is shown in Fig. 9. The actual structure being tested consists of other components which leads to the finite bandwidth but at the operating point of 11.4 GHz, the agreement is very close.

Fig. 10 shows a more complicated structure which is a 7-cell X-Band accelerator section with input/output coupler cavities.. A detailed description of the work is reported elsewhere in this conference [7]. Finally, we like to point out that Kroll et al [8] have devised an analytic method to obtain the S parameters from the frequency-domain solutions.

Conclusion

Currently available codes running on powerful workstations already present to the RF cavity designer a viable design and analysis tool which complements if not replaces actual cold-tests. As the codes continue to be improved and the computers offer still better performance, numerical modeling of complex cavities and structures will become a routine design procedure as CAD already is in other engineering practices.

Acknowledgements

The author wishes to thank W. B. Herrmannsfeldt for his unequivocal support. Thanks are also due to N. Kroll, C. Ng and E. Nelson for their involvement in many aspects of the numerical modeling work reported here and to T. Lee, H. Deruyter and H. Hoag for providing the data on the measurements. The help from T. Weiland and F. Krawczyk with MAFIA 3.1 is appreciated.

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