AUTOMATED DESIGN OF COUPLED RF CAVITIES USING 2-D AND 3-D CODES *

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Abstract

Coupled RF cavities in the Accelerator Production of Tritium Project have been designed using a procedure in which a 2-D code (CCT) searches for a design that meets frequency and coupling requirements, while a 3-D code (HFSS) is used to obtain empirical factors used by CCT to characterize the coupling slot between cavities. Using assumed values of the empirical factors, CCT runs the Superfish code iteratively to solve for a trial cavity design that has a specified frequency and coupling. The frequency shifts and the coupling constant k of the slot are modeled in CCT using a perturbation theory, the results of which are adjusted using the empirical factors. Given a trial design, HFSS is run using periodic boundary conditions to obtain a mode spectrum. The mode spectrum is processed using the DISPER code to obtain values of the coupling and the frequencies with slots. These results are used to calculate a new set of empirical factors, which are fed back into CCT for another design iteration. Cold models have been fabricated and tested to validate the codes, and results will be presented.

1 CCT: 2-D METHOD

1.1 The CCT Code

The function of the CCT (Coupled Cavity Tuning) code [1] is to solve for the dimensions of the accelerating cavity (AC), the coupling cavity (CC), and the distance between the AC and CC, such that the structure achieves design frequencies and coupling, k. CCT obtains a self-consistent solution in which the structure is tuned to the design frequencies, and the effects of the coupling slot between the AC and CC are taken into account.

The CCT code controls the 2-D axisymmetric code, CCLFISH [2]. CCLFISH performs RF calculations for a cavity without a slot and tunes the cavity to a target frequency. The effects of the coupling slot are approximated as described below.

1.2 Semi-empirical Equations for Slot Effects

The coupling slot is modeled using theoretical approaches of Gao [3] and Greninger [4], which are based on the Slater perturbation theory. The theoretical equations are adjusted by empirical factors [1]. The functional form of the equations is:

$$\Delta f_{ac} = A_{fac} f_1\left(W, L, t, E_{ac}, H_{ac}, U_{ac}\right) \tag{1}$$

$$\Delta f_{cc} = A_{fcc} f_1\left(W, L, t, E_{cc}, H_{cc}, U_{cc}\right) \tag{2}$$

$$k = A_k f_2\left(W, L, t, E_{ac}, E_{cc}, H_{ac}, H_{cc}, U_{ac}, U_{cc}\right) \tag{3}$$

$$kk = A_{kk} f_3\left(W, L, t, |x|, H_{ac}, H_{cc}, U_{ac}, U_{cc}\right) \tag{4}$$

In the above, the Δf's are the frequency shifts in the AC and CC caused by the slot. k is the coupling coefficient between AC and CC. kk is the next nearest neighbor coupling coefficient between adjacent AC's. A_{fac}, A_{fcc}, A_k, and A_{kk} are empirical factors. W, L, and t are the width, length, and thickness of the slot. E and H are electric and magnetic field in a cavity, evaluated at the center of the slot. U is the stored energy in a cavity.

The accelerating π/2 mode frequency for the structure is the net frequency of the AC adjusted for the effects of the slot and next-nearest-neighbor coupling, given by

$$f_{\pi/2} = \frac{f_{fish} - \Delta f_{mesh} - \Delta f_{ac}}{\sqrt{1 - kk}} \tag{5}$$

where f_{fish} is the frequency calculated by CCLFISH, Δf_{mesh} is a correction for finite mesh, and Δf_{ac} is the frequency shift caused by the slot (Eq. 2). A similar equation, with kk = 0, is used to calculate the net frequency of the coupling cavity.

In Eq. (1-4), the four empirical "A" factors may be determined from cold model data, or they may be calculated from a three-dimensional analysis, avoiding the cost of cold models, as described herein.

1.3 CCT logic

CCT calculates a self-consistent solution using the following logic:

1. Guess at values for the tunable cavity dimensions.
2. Assume values of the cavity frequency shifts.
3. Using these frequency shifts, calculate the shifted CCLFISH target frequencies, f_{fish} from Eq. (5).
4. Run CCLFISH to tune the AC and CC to meet the shifted target frequencies, updating the dimensions.
5. Assume a distance between the AC and CC.
6. Calculate the geometry of the coupling slot.
7. Calculate the coupling coefficients k and kk.
8. Compare calculated k with target k. If not converged, adjust the cavity distance and go to Step 6.

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9. Calculate new frequency shifts. If the frequency shifts have not converged, go to Step 3.

2 HFSS: 3-D METHOD

2.1 Calculation of Modes and Dispersion Diagram using HFSS

Because of meshing problems with the 3-D code HFSS, the accuracy of its calculated mode frequencies is insufficient for design purposes. The 2-D code Superfish [2] is accurate enough, but it cannot account for the slot. By combining the two codes, one can have the best of both. It has been demonstrated that the accuracy of the *frequency shifts* calculated by HFSS due to coupling slots and slot chamfers is sufficient for design purposes. In addition, the shape of the dispersion diagram calculated by HFSS is predicted well enough that it can be used to extract nearest and next nearest neighbor coupling constants with accuracy sufficient for design.

The following procedure is used to calculate the needed cavity frequencies and dispersion diagrams:

- Four models are constructed: (1) ½ the accelerating cavity; (2) ¼ coupling cavity without vacuum port; (3) ¼ coupling cavity with vacuum port, and (4) the coupled system consisting of ½ accelerating cavity coupled to two ¼ models of the coupling cavity with vacuum port. Models are segmented to guide the automatic meshing in HFSS. The same segmentation is used in the coupled and uncoupled models.
- The frequencies of the uncoupled cavities without slots are calculated.
- The mode frequencies of the coupled system are calculated by applying periodic boundary conditions to the symmetry planes of the ¼ coupling cavities, simulating the modes of an infinite biperiodic structure. Phase shifts of 0^0, 90^0, and 180^0 are applied between the boundaries. The modes are plotted as a dispersion diagram (frequency vs. phase).

2.2 Evaluation of Empirical Factors for CCT

The dispersion diagram is represented numerically as a finite set of modes. A curve fitting program, DISPER, is used to fit a theoretical dispersion diagram of a biperiodic structure to these points. There are enough points on the dispersion diagram for use in extracting individual cavity frequencies (including slot), nearest neighbor coupling constants, and next-nearest neighbor coupling constants.

The frequencies and other parameters calculated by HFSS and extracted from the dispersion diagram are listed below:

$f_{0achfss}$ HFSS accelerating cavity frequency, no coupling slot.

$f_{0cchfss}$ HFSS coupling cavity frequency, no vacuum port, no slot.

$f_{0ccvphfss}$ HFSS coupling cavity frequency with vacuum port, no slot.

f_{achfss} Accelerating cavity frequency with slot

$f_{ccvphfss}$ Coupling cavity frequency with slot

k Nearest neighbor coupling constant, accelerating cavity to coupling cavity.

kk Next-nearest neighbor coupling constant, accelerating cavity to accelerating cavity.

The CCT A factors are determined from:

$$\Delta f_{achfss} = f_{0achfss} - f_{achfss} = A_{fac}\, f_1$$

$$\Delta f_{cchfss} = f_{0ccvphfss} - f_{ccvphfss} = A_{fcc}\, f_1$$

$$k = A_k\, f_2$$

$$kk = A_{kk}\, f_3 ,$$

Where f_1 through f_3 are defined by Eqs. (1-4).

3 EXAMPLE OF CAVITY DESIGN

This technique has been applied to the design of a cold model for CCL segment 283 of APT, a cold model that had already been built and tested. The following sections describe the original design, performed using assumed A factors, and a redesign using the 2-D/3-D iteration.

3.1 Initial Design Using CCT Alone

The original design objectives were to achieve a coupling of 5% and a π/2 mode frequency of 700 MHz. "A factors" were estimated from cold model tests of SNS cavities. With these A factors, CCT was used to calculate the geometry of the cold model. The model was fabricated, tuned, and tested. Table 1 compares the calculated design values to the experimental data for the state in which the coupling slot has been chamfered but the model has not received its final tuning.

Table 1: Initial Design vs. Experimental Data, 283 Cavity

	Initial design		Experimental data	
Design parameters	Design values	SNS A factors	Meas. values	Meas. A factors
π/2 frequency	702.302		701.468	
f_{ac} (freq. w/ slot)	704.180		703.612	
f_{cc} (freq. w/ slot)	695.911		695.464	
Δf_{ac}	11.477	.9000	11.947	.9369
Δf_{cc}	22.628	.8700	23.242	.8936
k, coupling	.0488	.9620	.04836	.9520
kk, NNN coupl.	-.00535	.7240	-.00651	.8800
AC diam. (in.)	11.310		11.310	
CC diam. (in.)	7.635		7.635	
AC-CC distance	8.321		8.321	

As expected, the results did not exactly match the design goals, but they were quite close. The biggest discrepancy was underestimating the value of kk, which lead to overestimating the π/2 frequency. By coincidence, the SNS A factors gave fairly good predictions.

Other studies with cold models have shown that the A factors are not constant but depend on the cavity configuration and the amount of chamfer applied to the coupling slot. 3-D analysis is needed to account for these effects.

3.2 Design Iteration Using CCT and HFSS

For this exercise, to obtain a design that can be compared directly with experiment, the design objectives were modified to reflect the frequencies and coupling actually measured: $f_{\pi/2}$ = 701.468 MHz, f_{ac} = 695.464 and k = .0483. In this way, without prior knowledge of the A factors, we can validate the 2-D/3-D approach by reproducing (a) the original design geometry and (b) the modified set of A factors that were determined experimentally.

The design iteration began with an arbitrary set of A factors, all equal to 1.0. CCT calculated the first trial design, which was input to HFSS to calculate the first analytical estimate of the A factors. A second iteration between CCT and HFSS led to a second estimate of the A factors. A final run with CCT gave the final cavity dimensions. Table 2 shows the sequence of A factors and the cavity dimensions obtained in the three CCT runs.

Table 2: Iteration of A Factors and Cavity Dimensions

CCT Iteration	1	2	3
A factors used	All A's = 1	HFSS 1	HFSS 2
A_{fac}	1.000	.920685	.919169
A_{fcc}	1.000	.873057	.871495
A_k	1.000	.968154	.965725
A_{kk}	1.000	.876015	.876467
AC diam. (in.)	11.303	11.317	11.317
CC diam. (in.)	7.629	7.640	7.639
AC-CC distance	8.354	8.340	8.337

The 2-D/3-D iteration converges to a new set of A factors, obtained with HFSS entirely by calculations, that do not depend on experimental data. When the cavities are designed by this method the geometry converges close to a configuration that, experimentally, produces the observed frequency and coupling.

3.3 Converged Design vs. Experiment

Table 3 shows a comparison of the converged design calculations and the experimental data. In this case, one would expect the values of the π/2 frequency, k, and f_{cc} to be identical because CCT reproduces the target design conditions. The more interesting parameters to compare are the derived values of f_{ac}, and kk.

Table 3: Converged HFSS / CCT Design vs. Experiment

Parameter	HFSS calcs	CCT calcs	Exper. data
π/2 frequency	703.450	701.468	701.468
k, coupling coeff.	.04824	.04836	.04836
f_{ac} (AC freq, slot)	705.642	703.671	703.612
kk, NNN coupling	-.00625	–.00629	–.00651

In the HFSS column, one can see the lack of agreement in the absolute frequency. However, as mentioned previously, HFSS does calculate the frequency shifts and coupling accurately. The agreement of f_{ac}, and kk between CCT and experiment is good. Using A factors generated solely by HFSS, the coupling slot is represented accurately by CCT.

4 CONCLUSIONS

The iteration between 2-D (CCT) and 3-D (HFSS) calculations provides a design equivalent to one in which 3-D calculations are used to model the slot rather than empirical correlations, but the iterations are much faster. The absolute frequencies calculated by HFSS are in error, but the frequency differences are accurate. The frequencies calculated by CCT and CCLFISH, with empirical corrections for the slot effects, are well within the tuning range. Using this approach, we believe we can avoid the cost and time of most cold models, reserving cold models for code validation with different cavity types.

5 REFERENCES

[1] P. D. Smith, "CCT, a Code to Automate the Design Of Coupled Cavities," presented at the XX International LINAC Conference, Monterey. CA, Aug 21-25, 2000, Los Alamos National Laboratory report LA-UR-00-3504.

[2] J. H. Billen and L. M. Young, "POISSON SUPERFISH," Los Alamos National Laboratory report LA-UR-96-1834 (revision March 14, 2000).

[3] J. Gao, "Analytical Formulas for the Resonant Frequency Changes due to Opening Apertures on Cavity Walls," Nuclear Instruments and Methods in Physics Research A311 (1992) 437-443, North-Holland Publishing Company.

[4] P. Greninger, "Next Nearest Neighbor Coupling from Analytical Expressions for the APT Linac," Proc. 1999 Particle Accelerator Conf., New York City (March-April, 1999).