SUPERCONDUCTING RF CAVITY FREQUENCY AND FIELD DISTRIBUTION SENSITIVITY SIMULATION

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Abstract

Frequency and electromagnetic field distribution sensitivity of a superconducting RF (SRF) cavity are the fundamental phyical paramethers in cavity and tuner design. At low temperature, the frequency sensitivity can be obtained by measuring prototype cavity, but it is not easy to test the filed distribution sensitivity. This paper presents and describes a simulation method combining ANSYS and SUPERFISH to calculate the cavity frequency and field distribution variation due to cavity's small deformation caused by mechanical force, radiation force, thermal expansion etc.. As an example, the simulation results of the frequency and field flatness sensitivity on the SNS cavities were confirmed by their test results.

INTRODUCTION

Mechanical tuner controls slow frequency drift of the SRF cavity by deforming the mechanical structure and reconstructing electromagnetic field profile in the cavity. The tuner changes not only the cavity frequency, but also cavity's field distribution in the frequency tuning process. The field distribution variation could mean the cavity field flatness and external quality factors' change. The measurements indicate the field flatness change is about 20%/MHz in SNS medium beta cryomodule at 2K [1].

The field flatness of the SRF cavity affects the net accelerating voltage, the peak surface field [2], Lorentz force detuning coefficient [3] and the external quality factors [1]. Therefore the SRF cavity's frequency and field distribution sensitivity due to cavity elastic deformation are the essential physical parameters in the cavity and tuner design. Generally, at low temperature, the cavity frequency sensitivity can be obtained by testing the prototype cavity, but it is not easy to test the cavity filed flatness sensitivity. To resolve this problem, this paper addresses a simulation method to calculate the cavity frequency and field flatness sensitivity by combining ANSYS and SUPERFISH. At the same time, this method can save the cost.

MECHANICAL ANALYSIS

The mechanical analysis is a basic means to know how the cavity shape varies under external force. Here we use the ANSYS code to analyze the cavity deformation for its precise structure analysis function.

ANSYS Mechanical Model Setup

In the ANSYS analysis model, the element SHELL51 is selected for the axially symmetry of the SRF cavity structure. The material property of niobium cavity assumes an elastic modulus of 1.13×10^{11}Pa (4K), a density of 8570kg/m^3, and a Poisson's ratio of 0.38.

Table 1: SNS medium β cavity SUPERFISH results.

Element order	Z (cm)	R (cm)	E (MV/m)	H (kA/m)	P (kPa)
⋮	⋮	⋮	⋮	⋮	⋮
56	5.480	3.788	6.94E-02	-3.29E-02	-1.00E-05
57	5.511	3.820	6.74E-02	-3.39E-02	-1.00E-05
58	5.543	3.852	6.31E-02	-3.50E-02	-8.00E-06
⋮	⋮	⋮	⋮	⋮	⋮

The frequency and field profile sensitivity are analyzed after the SUPERFISH cavity shape optimization. A simple ANSYS modeling method is using the SUPERFISH results (such as: elements, electromagnetic filed, radiation pressure etc.) directly to create model in ANSYS analysis. The SUPERFISH results on cavity surface element need to be expressed in a table (see Table 1) for the ANSYS program call. Here the Z and R are the coordinates of the element on cavity surface. E, H and P are the electric field, magnetic field and radiation pressure on the element, respectively. APDL (ANSYS Parametric Design Language) program reads the data from Table 1 and uses the element coordinates to create the cavity model.

Boundary Condition and Loads

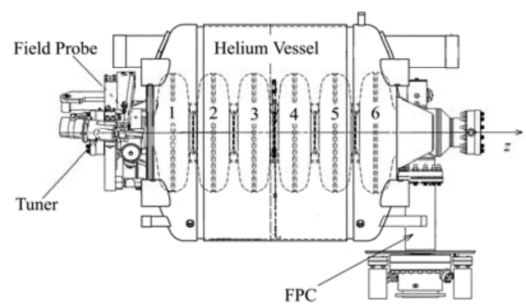

Figure 1: SNS cavity with helium Vessel.

In this paper, we use SNS type tuner as the example to demonstrate how to apply boundary condition and loads in ANSYS analysis.

The fundamental power coupler (FPC) is loaded on the beam pipe due to the high RF field in SRF cavity, for example, the SNS cavity (see Fig. 1). The FPC end is chosen as the fixed end. The other end is available to load the tuner, which changes cavity frequency by squeezing or stretching cavity along cavity axis. The frequency sensitivity is the ratio of the cavity frequency change Δf to the cavity longitudinal deformation displacement of the tuner pivot. So the displacement is the load. The cavity shape, wall thickness and reinforce rings are only relevant

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constraints. Combining these conditions, the ANSYS model is setup (see Fig. 2).

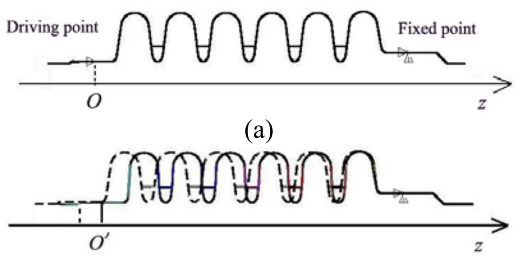

Figure 2: ANSYS model and its loads.

Solution and Result Output

A reasonable simulation range of the tuner movement is supposed to be 2.0 mm. The driving displacement of 0 mm corresponds to the cavity unloaded state. Because the output results of the ANSYS structure analysis will be used in SUPERFISH interaction simulation, they should compose of original and deformed coordinates of the elements and have the same sequence number as SUPERFISH has. Being sure that ANSYS simulation results are correct, we need to check the following results: 1. the deformed coordinates for 0 mm load; 2. the displacements for ±1.0 mm load.

Table 2: An SNS medium β cavity ANSYS T36 output file at 1.0 mm stretch

Element order	Z_O (cm)	R_O (cm)	Z_D (cm)	R_D (cm)
1	-21.6800	0	-21.6900	0
2	-21.6800	3.7875	-21.6900	3.7875
3	-21.5804	3.7875	-21.5904	3.7875
4	-21.4807	3.7875	-21.4907	3.7875
⋮	⋮	⋮	⋮	⋮

The deformed coordinates of the cavity elements can not be directly used to rebuild a new cavity in SUPERFISH. To precisely simulate the cavity frequency and field profile variation due to the small cavity deformation, the instruction ModT36 should be used in SUPERFISH simulation. This Instruction needs a separate file with extension .T36 to support it. So the output file of ANSYS APDL should have the same name as AUOFISH cavity file. The T36 file is shown as Table 2. Here the Z_O and R_O are the original coordinates of the elements, and the Z_D and R_D are the deformed coordinates.

SUPERFISH SIMULATION

The deformed cavity shape and unloaded cavity shape are input into the SUPERFISH code by using the AUTOMESH program with the mesh modification option "ModT36=1". The SUPERFISH can calculate newly tuned cavity's resonance frequencies and field distributions.

Frequency Sensitivity Simulation

Changing the load from -1.0 mm to +1.0 mm with step length of 0.1 mm in the ANSYS APDL file, each incremental file is obtained. Using these files and AUTOMESH program separately, the SUPERFISH can output the new cavity resonance frequencies and field distributions. The cavity frequency sensitivity is obtained from the SUPERFISH simulation outcome (see Fig. 3). As demonstrated in Fig. 3, the cavity's frequency variation is a linear to the cavity longitudinal displacement within the elastic deformation. The Frequency sensitivity *Ks* for a SNS medium β cavity is 296.16 kHz/mm. The test result of this coefficient is about 272.2 kHz/mm. The difference is about 8%. This error is acceptable in the tuner design.

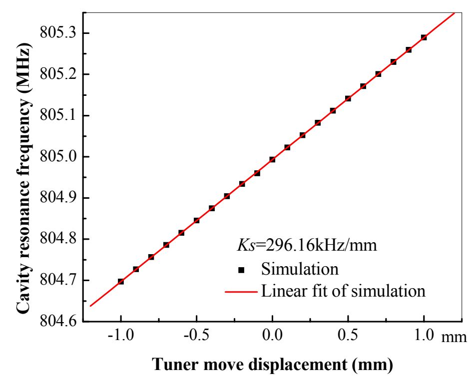

Figure 3: SNS medium β cavity Frequency sensitivity *Ks*.

Field Flatness Sensitivity Simulation

The original definition of the N-cell cavity field flatness η_{ff} is:

$$\eta_{ff} = \frac{V_{c\max} - V_{c\min}}{\frac{1}{N}\sum_{i=1}^{N} V_{ci}} \times 100\% \tag{1}$$

Here V_{ci} is the accelerating voltage of ith cell. $V_{c\max}$ and $V_{c\min}$ are the maximum and minimum cell voltage in the cavity, respectively. Using the relation between the V_{ci} and the peak electric field E_{ci} at the beam axis in the ith cell, the equation (1) becomes [4]:

$$\eta_{ff} = \frac{E_{c\max} - E_{c\min}}{\frac{1}{N}\sum_{i=1}^{N} E_{ci}} \times 100\% \tag{2}$$

The E_{ci} can be found from the axial electric field profiles of SUPERFISH output shown in Fig. 4. Submitting the cell peak fields into equation (2), the cavity field flatness is obtained. Fig. 5 shows that the field flatness is linearly increased due to the tuner movement, and its shape could be a symmetric "V", if the initial cavity field flatness is good enough. In contrast, Fig. 5 would not be a symmetric "V" shape, if the initial field flatness is very bad. The field flatness could change along one side of the "V" shape in a small frequency change range. Fig. 6 shows the field flatness change of a SNS medium cavity with initial field flatness of 26%.

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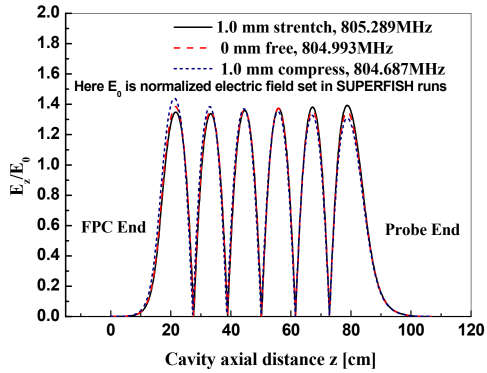

Figure 4: SNS medium β cavity axial field profiles.

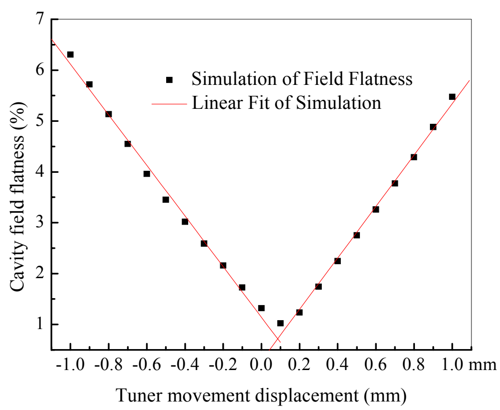

Figure 5: Field flatness variation for tuner movement. The initial field flatness at free status is 1.32%.

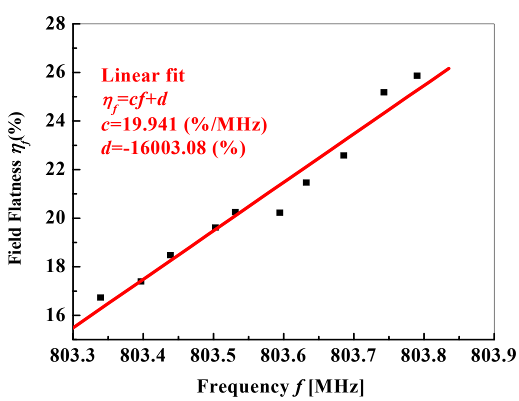

Figure 6: SNS MB19 cavity's field flatness for cavity frequency by bead pulling measurement. The initial field flatness is 26%.

The simulation shows that the SNS medium β cavity's field flatness variation rate is about 2% per 100 kHz tuner frequency change, and the field amplitude tilts linearly to the distance between the cell center and the cavity's geometry center [4]. The tilting rate has been measured in a cryomodule cold (2K) test, being about 2% per 100 kHz, relative to the field flatness at the cavity's center frequency of 805MHz. The bead pulling measurements confirmed that the field flatness change is 2.0% per 100 KHz for a SNS medium β cavity with the helium vessel.

DISCUSSION

The test results show that the simulation method combining the ANSYS and SUPERFISH is a precise tool to simulate cavity frequency and electromagnetic field change due to the elastic deformation. In practice, this method can be used to calculate any cavity frequency and field distribution change due to cavity's small deformation caused by mechanical force, radiation force, or thermal expansion etc. For example, if we change the load to the radiation force and fix the both sides of the cavity in the ANSYS APDL program, the static Lorentz force detuning coefficient K will be obtained. Fig. 7 illustrates the simulation result of the static Lorentz detuning coefficient K change due to the cavity field flatness change. This simulation agrees with the theoretical calculation of the reference [3].

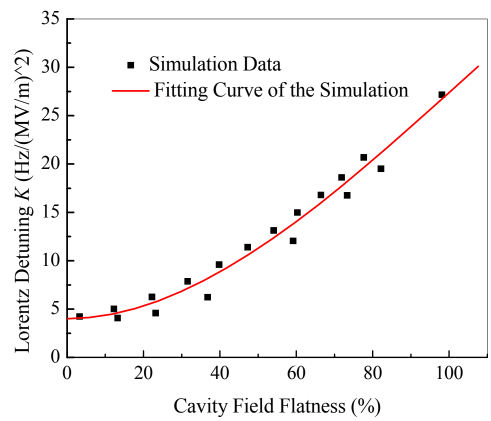

Figure 7: SNS medium β cavity Lorentz detuning coefficient K for field flatness.

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