THE COMPLETE 3-D COUPLED RF-THERMAL-STRUCTURAL-RF ANALYSIS PROCEDURE FOR A NORMAL CONDUCTING ACCELERATING STRUCTURE FOR HIGH INTENSITY HADRON LINAC

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Abstract

The design of high intensity proton linacs with high RF duty factor or cw operation requires critical evaluation of a 3-D coupled RF-thermal- structural-RF analysis for a normal conducting accelerating structure. The problem of heat removal from a normal conducting proton linac structure sets a limit on the operational RF duty factor. Therefore it is very important for a normal conducting high current proton linac structure to be analyzed as precise as possible for structural stability if it has to be operated at mush higher heat loading. A detailed procedure has been developed by performing a series of coupled analysis of rf-thermal and structural behavior using a single Finite Element software (ANSYS) environment. The appropriate constrain conditions in the structural analysis are of primary importance, a special procedure to establish the correct displacement values for the equilibrium conditions for the longitudinal structural expansion are also explained. The possible shift in the RF frequency due to non-uniform heating of the structure is also described. The particularities of the transient thermal behavior of the structure are discussed.

1 INTRODUCTION

For the operating regimes of the modern proton linacs with high duty factor or cw operation the heat loading to the structure due to rf power dissipation in the surface of the normal conducting cavity reaches the values, never realized before. The coupled analysis of effects, related to the nonuniform structure heating, becomes the necessary point in the accelerating structure design. The modern Finite Elements (FEM) software (ANSYS) allows us to perform such analysis being inside single environment and last time there are a lot of reports, dedicated to the thermal-structural analysis of accelerating cavities. The complete analysis of normal conducting Coupled Cells Structures (CCS) for hadron linacs has some particularities, related both to the operating linac regime and to the structure design. With the operating frequency $f_0 \leq 1000MHz$ (the skin-depth $\delta \geq 3\mu km$, accelerating gradient $E_0T \leq 4MV/m$ and enough long rf pulse $\geq 100\mu ks$ we do not interesting with pulse surface heating, as compared with the normal conducting structures for linear colliders, and should concentrate on average values. Analysis of superconducting structures has its own particularities. In this report the procedure for the coupled analysis, developed during the structure design of the CCS part of the KEK/JAERI joint project linac, is presented. The set of topics, considered in the analysis, and some improvements allow to consider it as the most general procedure now for the topic determined.

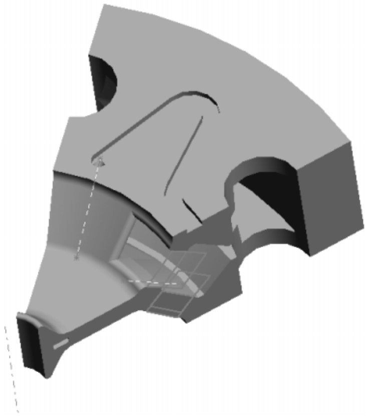

Figure 1. The solid model of the ACS structure for the coupled analysis.

2 THE SOLID MODEL

The solid model development and the problem regions meshing is the first step in the analysis. For solid model creation there are different possibilities [1], [4]. We use [5] the SOLIDWORK software. The problem symmetry should be used as possible to decrease the physical dimension and to use the smallest mesh-size for the given computer capacity. Differing from another RF software, ANSYS allows to apply necessary boundary conditions wall at sloped planes [1]. In Fig. 1 the solid model for the periodical Annular Coupled Structure (ACS) analysis is shown, allowing analysis both for operating and for coupling mode [6]. In the solid model such attractive simplification as sharp corners (to simplify the geometry description) should be avoided as possible - it may be reasons for numerical errors in analysis.

3 RF ANALYSIS

The procedure of the cavity RF analysis in ANSYS becomes now well known and the sequence of operations is described in [2], [1], [5]. The procedure of the heat flux calculations and transfer the thermal analysis is realized with intermediate surface elements, similar to [1]. At this step we recommend the qualitative check of the calculated heat flux distribution, at least in 'hot points' . Original variables for ANSYS RF analysis are the components of the electric field $\vec{E}$ and magnetic field is obtained as numerical derivatives. In the FEM technique the precision of derivatives calculations depends strongly on the mesh quality.

4 THERMAL ANALYSIS

After the heat flux transfer as external load the procedure of the thermal analysis is fine developed in ANSYS and can be performed in usual way. Below we describe some particularities of the analysis for CCS with strong heat loading. In our investigations [5] the recommendation for the cooling circuit design was developed - the channels cross-section should be chosen to keep the flow rate nearly constant. With the cross-section increased only in a part, the fluid velocity drop can lead to the film coefficient reduction and total cooling efficiency decreasing.

4.1 RF losses increasing

If the steady-state temperature distribution $T(\vec{x})$ in the structure body is obtained, one can easy estimate the rf power dissipation increasing due to surface temperature increasing. Usually the material surface resistance R_{s0} is defined for some reference temperature $T_{ref} \sim 0C^o$. For practical $T(\vec{x})$ values we assume the linear dependence of the local surface resistance R_s on the temperature:

$$R_s = R_{s0}\sqrt{1+\eta\delta T}, \quad \delta T = T(\vec{x}) - T_{ref}, \quad \eta = 0.0039[1]/[C^o].$$

The relative rf losses increasing can be estimated easy:

$$\frac{P_s^{cor}}{P_s} = \frac{\int_{S_1}(\sqrt{1+\eta\delta T})H_\tau^2 dS}{\int_{S_1} H_\tau^2 dS}, \tag{1}$$

where S_1 is the structure vacuum-metal surface. Some times the "hot spots"- regions with the higher surface temperature coincides with the regions of high rf losses density [3], [5] and the effect of the rf losses increasing may be of order of several percents.

4.2 Transient thermal analysis.

The transient thermal analysis can be performed in a usual way. With the particularities of the hadron linac regime, we can neglect the pulsed structure of the surface heating and apply the average heat load as a step-up function. The main reason for the transient thermal analysis are hesitations for the maximal stress values. Our consideration shows the maximal stress values take place during steady-state regime. This conclusion coincides with the results of another work [4] and can be explained qualitatively.

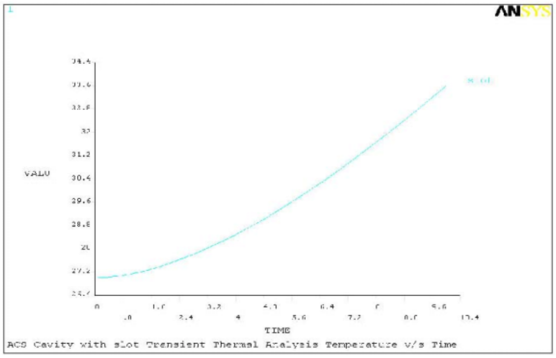

Figure 2. The temperature raise of the structure portion with maximum temperature (for steady-state) region.

Let consider so small volume of material δV that we can consider the temperature gradient $\vec{g}radT$ as one- dimensional $\frac{\partial T}{\partial l}$. Considering the heat propagation equation, one can conclude - the heat flux through the volume δV surface during transient can not exceed one in steady state regime. The stress value σ can be estimated as $\sigma \sim E\frac{\partial T}{\partial l}$, where E is the Young module. If the local temperature T rises in time, the gradient value $\frac{\partial T}{\partial l}$ and stresses are less than steady state ones. At the Fig. 2 the temperature raise of the structure portion with maximum temperature (for steady-state) region [5] is shown. The same consideration is valid also after rf power switch-off. One have to examine transient in more detail only if there are temperature oscillations in the material. For step-up heating the temperature oscillation are not possible for the first (in time) order equation od heat propagation.

5 STRUCTURAL ANALYSIS

The correct constrain definition is of primary importance to define the correct values for displacements (so, the frequency shift evaluation) and stress. For the part of the periodical structure (Fig. 1), the constrains definition at the outer surface and at longitudinal symmetry planes is clear - a free boundary in first case and no perpendicular (to the symmetry planes) displacements in the second one.

5.1 Longitudinal constrains definition.

In the expansion due to heating (even nonuniform, but periodical) the periodical structure must expand so, that the boundary between periods all time remains the plane and the period length increases at unknown value dx_{un}. To define dx_{un} value, the following method is proposed.

Let simulate for the one period of the structure (Fig. 3) the structural problem with next constrains - $dx = 0$ at the left (bottom in Fig. 3) side of the period and free expansion for right (top) boundary. Due to nonuniform structure period heating the longitudinal expansion is also nonuniform at the right plane and let define the values of minimal $dx1$ and maximal $dx2$ longitudinal displacements (Fig. 3).

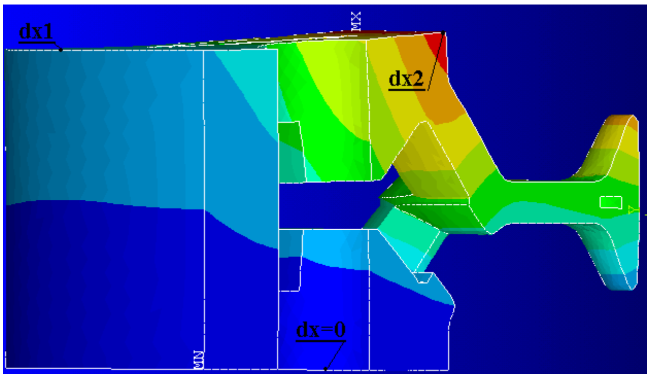

Figure 3. The structure nonuniform longitudinal expansion in the case of the free upper boundary. The structure axis x is down to up.

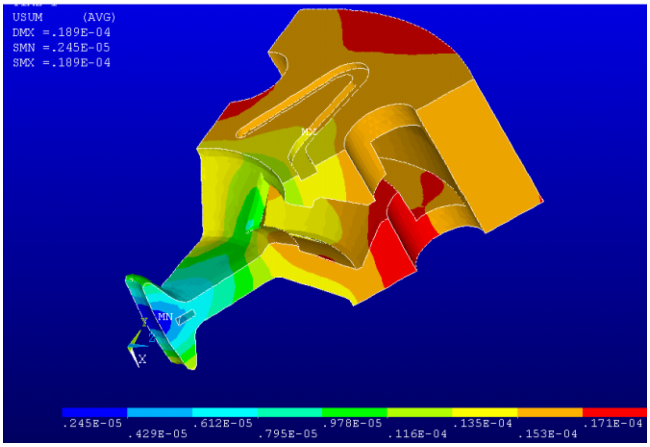

Figure 4. The distribution of the total displacements for ACS with 15% duty factor, $\beta = 0.5581$.

Than perform second and third simulations with all time fixed $dx = 0$ left side and enforced displacement $dx1$ (second) and $dx2$ (third) for right side as a whole plane. In these runs we need to define the total longitudinal force $F_x^{(1,2)}$ as:

$$F_x^{(1)} = \int_S p_x dS|_{dx=dx1}, \quad F_x^{(2)} = \int_S p_x dS|_{dx=dx2}. \quad (2)$$

The F_x value linearly depends on the enforced displacement value and the corresponding to equilibrium condition ($F_x = 0$) value dx_{un} is:

$$dx_{un} = \frac{F_x^{(2)} dx1 - F_x^{(1)} dx2}{F_x^{(2)} - F_x^{(1)}}, \quad dx_1 < dx_{un} < dx_2. \quad (3)$$

With the such procedure we found the real equilibrium conditions, when the outer part of the structure (with lower expansion) balance the hot inner part with a larger longitudinal expansion.

5.2 *Frequency shift determination.*

Even in the case of the strong heat loading the typical surface displacement values (see Fig. 4) are $\sim 10 \mu km \approx 10^{-5} m$. It is very small value in comparison with the typical structure dimensions $\sim 10^{-1} m$ and relative frequency shift $\frac{\delta f}{f}$, caused by displacements, is also very small. It is not evident, that the precision of the FEM geometry approximation and eigen-value problem solution for 3-D simulation, is sufficient to determine such small value and perturbation method is more consistent. To use only quantities, calculated in ANSYS, we use the perturbation method in the form:

$$\delta f = \frac{\pi f^2}{2QP_s} \int_{S_1} (\epsilon_0 E^2 - \mu_0 H^2)(d\vec{x}\vec{n}) dS, \quad (4)$$

where E, H are the electric and magnetic fields at the structure surface S_1, $d\vec{x}$ - is the surface node displacement, $\vec{n}$ is the unit normal vector to the surface, Q, P_s are the quality factor and rf losses (corresponding to H current normalization), calculated before.

6 PROCEDURE REALIZATION

The data exchange between RF and thermal analysis is realized with intermediate surface elements [1] with some modifications. For another estimations (1), (4) we have two options. First option is realized in ANSYS command language and works slowly. For the fast second option we withdraw all information necessary (nodal coordinates, field, temperature and displacement values) from ANSYS data base into special text file and treat it with the developed MS Fortran routine.

The parts of the procedure described were used in the beginning [5] of the structural analysis of the ACS structure for JAERI/KEK Joint Project. In the final complete form it was applied into investigations of the ACS accelerating module power capability [6]

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