THERMAL DEFORMATION MODELLING ATTEMPT OF A STORAGE RING VACUUM VESSEL

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Abstract

This paper deals with the finite element modelling (FEM) of a storage ring vacuum vessel. The geometry and heat load distribution of the ESRF storage ring have been used in the FEM. The mechanical fixtures of the vacuum vessels are not modelled due to their complexity. Sub-structuring technique, an advanced FEM technique, was used to handle the large assembly. Finite element results showed that the pure thermal deformation of such a cell (not constrained) could reach 37mm in lateral displacement, and this displacement could be reduced to 2.3mm with mechanical supports at appropriate places. Influences of the stiffness of bellows were also studied.

1 INTRODUCTION

In a 3rd generation synchrotron radiation source, Insertion Devices (ID) are essential photon beam sources for beamlines. A small portion of synchrotron radiation from bending magnets is also used in beamlines. At the ESRF, the total power of bending magnet radiation reaches 1 MW at I=200mA, more than 85% of this power is absorbed by thermal absorbers located inside the storage ring vacuum vessels. The design of thermal absorbers and vacuum vessels is crucial since they should withstand the high heat load and induce limited thermal deformation of the storage ring. Finite element modelling has been widely used in the design of these absorbers and vacuum vessels, especially for the 3rd generation synchrotron radiation sources. As far as we know, the FEM has been made only for some individual vessels and absorbers.

The thermal deformation of the vacuum vessel is generally managed with numerous bellows, which allow both longitudinal and lateral deformation. The lateral and longitudinal deformations of the vessels are partially prevented by the use of mechanical supports. However, the design of the mechanical supports and selection of bellows are often approximate. In practice, mm-order of lateral displacement of the vacuum vessel can be observed. This large lateral displacement induces some problems for the position stability of magnets and BPMs. To better understand the mechanical behaviour and smartly control the thermal deformation of a storage ring as a whole, it is interesting to study a large assembly of the storage ring. In this paper, we will present a finite element modelling of a full standard cell of the ESRF storage ring vacuum vessel with ANSYS. The FEM will be concentrated on the vacuum vessels and absorbers. Different simple constraint conditions and stiffness of bellows will be investigated. The real fixtures and supports are not the subject of this study. Normally the radiation beam generated by insertion device is only collimated in front-end and in beamlines, and does not touch thermal absorbers located inside the storage ring vacuum vessels. Thus, only the heat load from bending magnets was considered in the FEM.

2 FINITE ELEMENT MODELLING

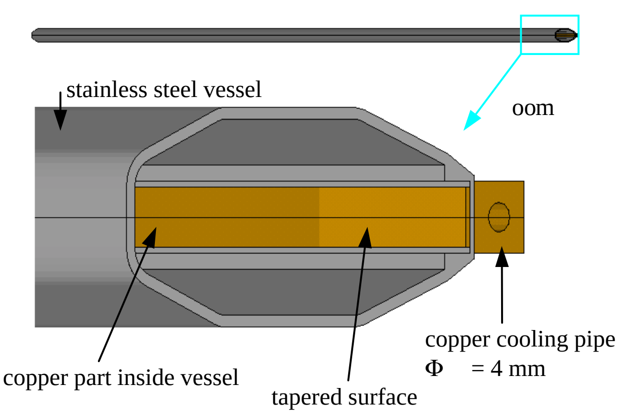
2.1 A cell of storage ring

The ESRF storage ring consists of 32 identical cells, except the injection and extraction regions, the RF acceleration regions. A standard cells contains dipole vessels (CV05, CV12), crotch vessels (CV06, CV13) and absorbers, bellow flat absorbers with vessels (CV07, CV14), straight section vessels and distributed absorbers (CV03, CV04, CV08, CV09, CV10, CV11, CV15), insertion device vessels, and numerous bellows [1]. There are 3 types of thermal absorbers : crotch absorbers in CV06 and CV13, flat absorbers in CV06, CV07, CV13, CV14, and distributed absorbers in all straight section vessels. Crotch absorbers are those dissipating slightly more than 50% of synchrotron radiation power from bending magnets, and were intensively studied in all the 3rd generation synchrotrons. The specific FEM of crotch absorber is not the subject of this study.

2.2 FEM of a straight section vessel

The geometry of a straight section vessel with distributed copper absorber is shown in Fig.1. The length and angle of the tapered surface could be different from one straight section vessel to another. The heat load on the absorber of these vessels is different since the distance between these vessels and bending magnets is different. The length of the vessels varies from L=620 mm for CV04 to 2154 mm for CV03A. The height of the photon beam on the absorbers is typically w_{bm}=1 mm, larger than 1 mm for CV03 and CV04, but less than 1mm for other straight section vessels. The large ratio of L/w_{bm} implicates large number of nodes and elements. The difficulty in the FEM is trying to both limit the total number of nodes and elements, and to make a thin enough meshing in the area

Fig.1 Finite Element Model of a straight section vessel



of high temperature and stress gradients, usually in the area with heat load. So variable-meshing size is frequently used. Despite efforts made for the meshing and modelling, the finite element model is still very large. But the computer sources can handle the analyses of each individual vessel with thermal absorber. However, it is difficult or impossible to model one complete cell of storage ring vacuum vessels with thermal absorbers in standard finite element method. We will use the so-called sub-structuring technique to perform the FEM for a large number of vessels in one cell.

2.3 FEM of a cell with sub-structuring

Sub-structuring [2] is a finite element analysis procedure that condenses a group of finite elements into one element represented as a matrix. This single matrix element is called a super-element. The huge number of nodes is reduced into a set of master degrees of freedom, which are mainly used to define the interface between the super-element and other elements or super-elements. An example of super-element is shown in Fig.2 for the flat absorber and CV07 vessel. The "regular" finite element model contains 66711 nodes and 54433 elements, the condensed super-element (1 element) associates 206 nodes (masters). The master nodes are on end sections that allow the links with adjacent vessels. Some nodes along the vessel between the 2 end sections are also introduced as masters in order to have directly the deformation results without doing expansion pass that calculates the results at all nodes in the "regular" finite element model. The advantages for sub-structuring are (i) to reduce computer time and (ii) to allow solution of very large problems with limited computer resources.

Fig.2 Flat absorber and CV07 vessel : finite element model, super-element and masters

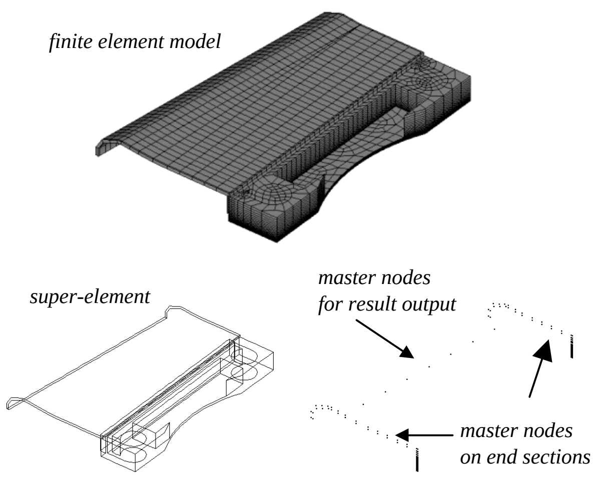
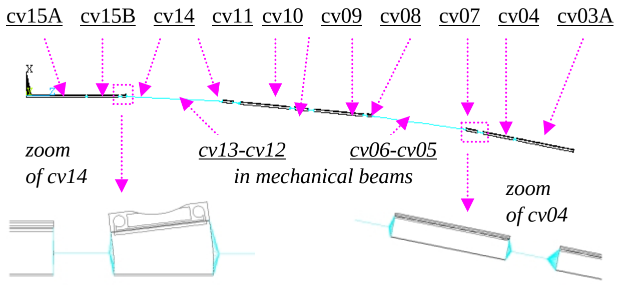


Fig.3 Finite Element Model of a cell of storage ring, *vacuum vessel and thermal absorbers are in super-element*



In practice, a complete thermal analysis has been performed for each vacuum vessel and associated thermal absorber with the "regular" finite element model. Interaction between vacuum vessels is only mechanical. Heat transfer between different vessels is negligible. The calculated temperature distribution, as well as symmetrical mechanic boundary conditions, was considered in the super-element generation. All super-elements are then assembled (Fig.3). All the straight section vessels with distributed absorbers were modelled in details and condensed in super-element, as well as bellow flat absorbers within vessels. The crotch vessels are very compact compared to other vessels, the design of the ESRF crotch absorbers was made so that the deformation of the vessels is negligible. These vessels are welded on the rigid dipole vessels that do not contain absorber and don't deform in consequence. In the FEM of the cell, the crotch and dipole vessels were simplified by mechanical beams, of which the moment inertia was calculated based on the geometry of the vessels. Flanges used to connect vessels are very rigid compared to vacuum vessels. They are modelled with a special combination of mechanical beam [3], which are not deformed but correctly transmit deformation between vessels. Bellows have been widely used to absorb the longitudinal and lateral deformations of vacuum vessels following the thermal expansion due to either vacuum bakeout or synchrotron radiation heating. These bellows are modelled using mechanical beams with correct axial and lateral stiffness from supplier's data sheet. As the geometry of ID vessels varies very much with different sections, different materials, different gaps and length, we will not consider ID vessels in this study. However, there is no difficulty to model ID vessels and to take into account in the FEM of a cell of storage ring.

3 FEM RESULTS AND DISCUSSION

In this study we have fixed two objectives (1) feasibility demonstration of finite element modelling and (2) prediction of thermal deformation of a cell of storage ring vacuum vessel. The geometry and heat load distribution of the ESRF storage ring have been used in the FEM. But the mechanical fixtures of vacuum vessels are not modelled due to their complexity. The idea is to study the influences of fixtures with simple mechanical boundary condition. As we focus on the thermal deformation, the differential pressure effects were not considered.

First investigated point is the mechanical boundary conditions. The one cell of storage ring vessel was assumed to be fixed at the two ends. This is a simplification of periodic boundary conditions at the two ends. Additional fixed points have also been introduced : 1 point on each of the two crotch vessels fixed in lateral direction (+1Ux/crotch) or in both lateral and axial directions (+1UxUz/crotch), 2 points on each of the two crotch vessels fixed in lateral direction (+2Ux/crotch) or in both lateral and axial directions (+2UxUz/crotch). Computed results are plotted in Fig.4 in forms of deformed shape with comparison to non-deformed shape. The non-deformed shape was plotted with the co-ordinates (x_0, z_0) of the vessels Deformed shape (x, z) was reconstructed from the non-deformed shape (x_0, z_0) and computed deformation (Ux, Uz) as following : $x=x_0+f_a*Ux$, $z=z_0+f_a*Uz$, where f_a is an amplification factor used only for visual purpose. Maximum lateral displacements are given in Table 1. The scaling factor f_K was used to vary lateral and axial stiffness of the bellows. The axial and lateral stiffness of bellows at $f_K=10$ are 10 times as high as at $f_K=1$. Results shown in Fig.4 correspond to $f_K=1$. If one cell of storage ring were fixed at the 2 ends (more or less equivalent to free boundary condition), the lateral displacement would reach 37 mm.

Fig.4 Deformed shape of one cell of storage ring vessel

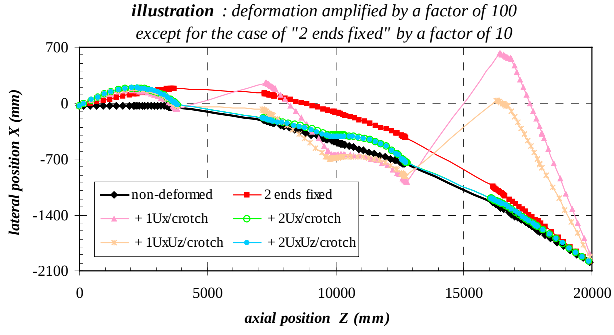


Table 1 Maximum lateral displacement of a cell of storage ring vessel, unit in ***mm***

scaling factor f_K	0.5	**1**	2	10	100
2 ends fixed	37.0	**37.1**	37.2	37.2	37.0
+1Ux/crotch	18.7	**18.8**	18.8	19.1	21.6
+2Ux/crotch	2.2	**2.3**	2.3	3.3	13.3
+1UxUz/crotch	12.9	**12.9**	12.9	13.0	13.4
+2UxUz/crotch	2.3	**2.3**	2.3	3.3	10.4

This displacement can be reduced to 2.3 mm with 2 additional fixed points on each crotch vessel. Two points fixed on the crotch vessel prevent rotation of the crotch vessel. This is not the case with only one point fixed. That’s why the lateral displacements in the cases of 1 additional point fixed on the crotch vessel are much larger than in the cases of 2 additional points fixed on the crotch vessel. Note that the deformation of vacuum vessels is not very sensitive to the stiffness of the bellow. Only if this stiffness were 10 times higher than the used bellows, the thermal deformation could be significantly higher. In general, “soft” bellows collect better thermal deformation, and the storage ring vessel deforms less in consequence. It should be mentioned that the real mechanical fixtures of vacuum vessels at the ESRF are much more complex than the boundary conditions (fix points) in the FEM. The real deformation of vacuum vessel should be significantly smaller than the values of deformation mentioned above.

4 CONCLUSION

This study showed the feasibility of predicting the thermal deformation of a storage ring vacuum vessel with FEM. Sub-structuring technique is adequate to handle a large system. Thermal deformation of storage ring vacuum vessels can be minimised by using appropriate fixtures. This is very interesting for optimising the location of BPMs, for defining the space between vacuum vessels and magnets, etc.

We have performed FEM on one cell of a storage ring vessel without ID vessel. It is possible to make FEM for a full storage ring vessel with all ID vessels.

REFERENCES

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