MODELING OF FLEXIBLE COMPONENTS FOR ASSERTING THE STABILITY OF SUPERCONDUCTING MAGNETS

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Abstract

Superconducting magnets are subjected to various forces during their cool down and alignment. A good estimate of the deformations arising out of the cool down and alignment operations is necessary as these induce relative displacements between the fiducialised external vessel and hidden cold mass of the magnet. The non-linear and orthotropic behaviour of these elements may make the model complicated and if solved as a non-linear problem, would entail a large solution time a s the overall model size runs into millions of nodes. The authors developed a unified Finite Element Model of the LHC Short Straight Section and during this process many innovative modelling techniques evolved. The developed model uses isotropic material constitutive laws with linear material properties. This paper presents some of the salient features of these modelling techniques.

INTRODUCTION

The Short Straight Section (SSS) (Figure-1) can be structurally divided into two main parts: the external vacuum vessel and the internal cold mass of the magnet.

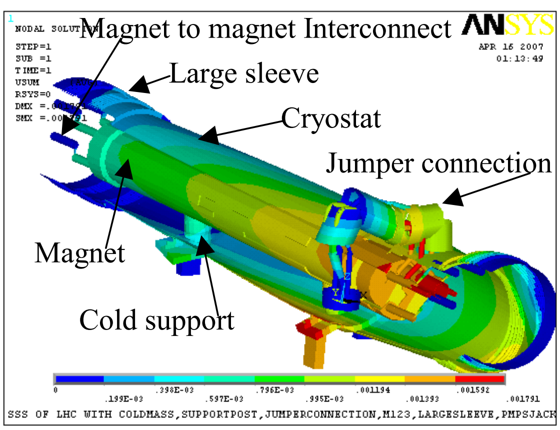

Figure 1: A view of the Short Straight Section Model.

The external vacuum vessel is a 6 mm thick cylindrical vessel with a diameter of 910 mm and a length of 6480 m. One end of the SSS has a service module which is an 8 mm thick vessel with a diameter of 1025 mm. Liquid and gaseous Helium are transported from the service module of the cryogenic distribution line to the service module of short straight section through a "Jumper Connection". The Jumper connection consists of some internal pipelines with flexible hoses and is covered with an external vacuum jacket. The Jumper is provided with two gimbals, one in the vertical segment and the other one in the horizontal segment. The external vacuum vessel of the SSS is connected to the adjacent magnets by "large Sleeves" having a length of 840 mm and diameter of 1077 mm. These large sleeves are large bellows to provide the flexibility between the magnets but they also have adequate inertia to provide circumferential stiffness against buckling. The cold mass of the adjacent magnets are connected through many flexible lines having bellows but three bellows M1, M2 and M3 have higher stiffness and they are the only bellows that are important from the point of view of restraining the cold mass elastic movements in lateral directions. Two composite support posts, support the cold mass of the magnet on the vacuum vessel. One of the composite supports is free to move in the longitudinal direction and can also lift upwards. The other support post is fixed to the cryostat. These support posts have orthotropic properties and exhibit different elastic behaviour in the lateral direction as compared to the axial direction.

FINITE ELEMENT MODEL

The objective of the calculation was to establish a relationship between the absolute position of the cold mass and the vacuum vessel when known displacements are applied to the alignment jacks. This calls for a finite element model that can model the stiffness of the entire structure with all its peripheral components.

The finite element model of the SSS consists of beam, shell, bar and solid elements (Table-1). Appropriate constraint equations have been used to attach these elements together.

The stiffness modelling of the flexible members (bellows and hoses) is based on a secant modulus approach. So, the solutions are not valid through the entire range of displacements. The solutions have been obtained at discrete points and they have been compiled together by a coefficient matrix that defines the relationship between jack movement and cold mass absolute position for each jack displacement value.

Since the structural members of the developed model vary in their stiffness by orders of magnitude, guarding against ill conditioning is a major issue. The numerical model was verified by conducting sensitivity tests against suspected stiffness values and wherever, ill conditioning was noticed, the model was reviewed and appropriate constraint equations/coupling were implemented. In general, we have used constraint equations and node to node coupling in place of prescribing high stiffness values.

Definition of an orthotropic material model involves definition of a large number of material properties (Young's modulus, shear modulus and Poisson's ratio in all three directions), therefore equivalent isotropic

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1-4244-0917-9/07/$25.00

material models have been developed which agree with the measured values of stiffness in all the directions.

Table-1: Elements Used in the FE Model

Component	Description
Cold Mass	Brick elements (SOLID45) for modeling the mass. Shell elements (SHELL63) for modeling the external shrinking cylinder called inertia tube.
Cryostat & Large Sleeves	Shell (SHELL63) elements.
Cold Supports	Combination of shell and bar elements
Interconnection Bellows	Beam elements (BEAM4) to model the secant stiffness of non-linear load displacement curve.
hoses, gimbal & horizontal bellow of jumper	Beam elements (BEAM4) and constraint equations to model secant stiffness and hinge friction of non-linear load displacement curve .
Alignment Jacks	Beam elements (BEAM4) with constraint equations

MODELING TECHNIQUES

Cold Support

The GFRE (Glass Fibre Reinforced Epoxy) material of cold support follows orthotropic material properties and therefore shows different stiffness in lateral and axial directions. Getting consistent orthotropic properties was a tedious task and therefore, a different scheme based on the experimental observation of stiffness in lateral and axial directions is used. The cold support is modeled with a combination of shell and bar element. The bar element is aligned along the axis of the cylindrical shell structure. The ends of the link are coupled with the end nodes of the cylindrical shell through a rigid region connection (Figure-2). The appropriate shell thickness along with isotropic Young's modulus provides the entire lateral stiffness whereas the axial stiffness is shared between the bar element and the shell elements. This ensures the stiffness modeling of orthotropic composite material behavior of the support post with isotropic definitions.

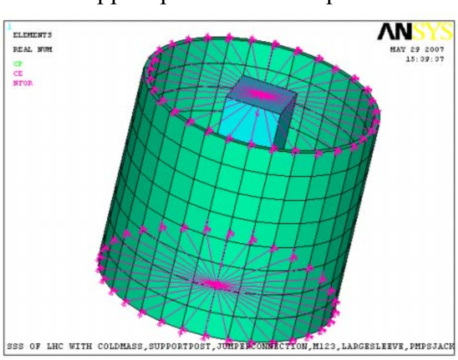

Figure 2: FE model of Cold support.

The free longitudinal movement of one of the support posts is modelled by leaving that degree of freedom uncoupled from the base (Figure-3). No constraints equations are required for nodes at the shell-solid interface as the solid pad provides a comparatively rigid (clamped) boundary condition for the shell elements and therefore the shell elements would not see rotation.

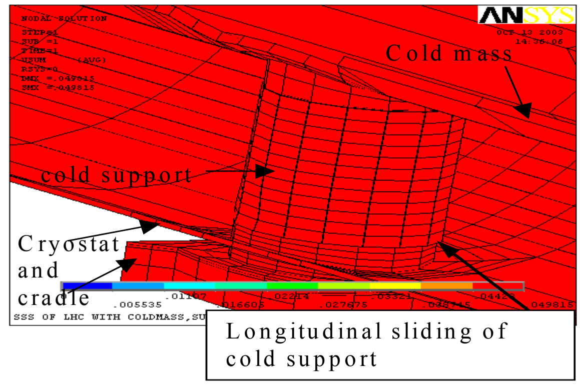

Figure 3: Cold Support and the sliding behaviour in longitudinal direction.

Metal Hoses

The bending stiffness of the metal hoses have been provided by using general beam elements (BEAM4). This element has provision of defining all the three stiffness (axial, bending and torsional) separately.

The bending stiffness is modelled by specifying appropriate secant modules and moment of inertia. The axial stiffness can be specified by providing an appropriate cross sectional area. The non-linear load displacement characteristic of the hose is approximated by bilinear load displacement curves. In the first run, the secant stiffness from the load-displacement characteristics is selected based on the initial estimated displacement. In a subsequent run, the program selects an appropriate stiffness depending on the calculated displacements in the first run. This two-step process eliminates the need for a full non-linear analysis. This scheme is sufficiently accurate as the initial stiffness values are based on the experimentally validated model.

Vacuum Jacket of the Jumper Connection

The vacuum jacket of the jumper connection consists of two gimbals, one in the vertical segment and the other in the horizontal segment. Both the gimbals have hinges to allow bending of the bellows but they are quite rigid in the axial direction. We have provided a coupling between the end nodes of the gimbal to account for high axial stiffness. This technique helps in avoiding ill conditioning due to the presence of low bending stiffness and high axial stiffness. The bellows and intermediate pipe segments of the gimbals are modelled with beam elements. Angular and lateral stiffness were converted into equivalent moment of inertia so that the bellows' stiffness are correctly represented. The end of the

Jumper is connected to the vacuum vessel of the service module of the SSS through a rigid connection. Hinge friction adds to the reaction forces at the interface when the SSS is moved by operating alignment jacks in vacuum. This contribution can be accounted for by increasing the bending stiffness by an appropriate amount.

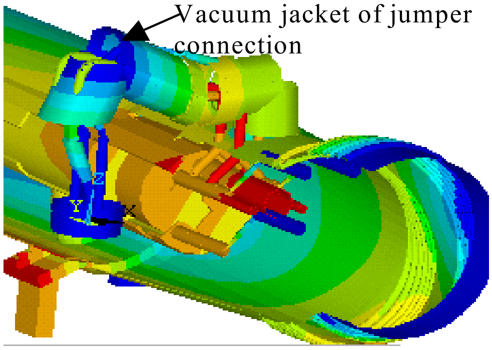

Figure 4: FE model of the Jumper Vacuum jacket.

Large Sleeve

The large sleeve has two bellows that need flexibility in bending and in the axial direction but shall have sufficient circumferential stiffness to guard against buckling. Deep corrugations provide the flexibility and shallow corrugations provide the required circumferential stiffness. The structure's behaviour is such that the deeper corrugations have good bending and axial flexibility and the shallow corrugations behave like a relatively rigid body. Since, our model required the specification of correct bending and axial stiffness, a systematic numerical experimentation was done to come out with a simplified shell model with a relatively small number of elements. The stiff part that plays no role during the elastic bending, is modelled by flat elements but the flexible corrugations are modelled with a greater number of elements.

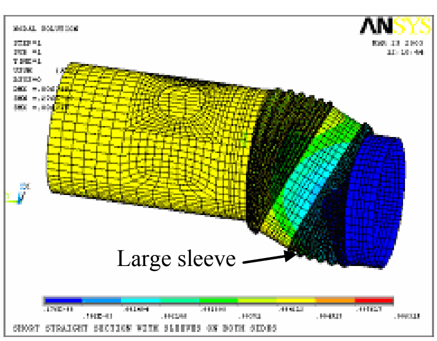

Figure 5: FE model of large sleeve.

Magnet to Magnet Interconnects

The free length of M1, M2 and M3 bellows is 95 mm. These bellows are pre-stressed by 16 mm during initial installation and are elongated by 30 mm during the cool down. A logic structure has been developed within ANSYS that uses correct length, stiffness and longitudinal forces arising because of a change in state of the magnet. The program logic is also capable of accommodating the misalignment due to manufacturing tolerances.

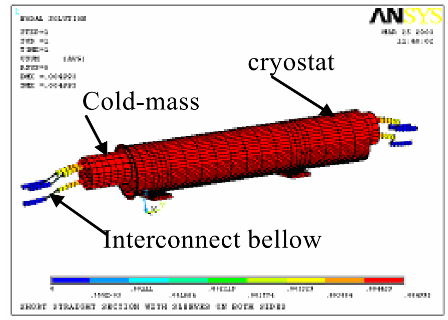

Figure 6: FE model of magnet to magnet interconnects.

CONCLUSION

The model developed was validated with experimental results and subsequently tuned especialy with respect to cold mass stiffness. The results are being used for the alignment of SSS during LHC installation.

The stiffness modelling explained in this paper is simple to implement and can be easily adapted for modelling similar structures having multiple components with orthotropic properties and large differences in their stiffness values.

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