STRUCTURAL ANALYSIS OF AN INTEGRATED MODEL OF SHORT STRAIGHT SECTION, SERVICE MODULE, JUMPER CONNECTION AND MAGNET INTERCONNECTS FOR THE LARGE HADRON COLLIDER

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Abstract

The Short Straight Section (SSS) of the Large Hadron Collider (LHC) may undergo relative displacements between cold-mass and cryostat for the following three reasons;

- Fabrication tolerance of interconnection bellows
- Global smoothing after pre-alignment
- Ground motion in a sector of the LHC tunnel

The forces responsible for such displacements stem from finite stiffness of interconnect bellows & metal hoses of the internal piping of the jumper connection and from relatively flexible 'glass fibre reinforced epoxy' (GFRE) composite supports of the cold mass. In addition, the vacuum jacket of the jumper connection and the large sleeves attached to both ends of SSS produce elastic deformations of the cryostat vessel. A unified finite element model consisting of cryostat, large sleeves, vacuum jacket of jumper, interconnection bellows, internal piping of jumper, composite cold supports and alignment jacks has been prepared.

The knowledge of the position of the cold mass with respect to its cryostat under various conditions of alignment done using external fiducials mounted on the cryostat is essential. The maximum relative displacement for satisfactory machine operation is 0.1 mm. An SSS with cryogenic jumper connection has been modelled with the aim of assessing this possible displacement.

INTRODUCTION

The cryostat outer envelope is a 6 mm thick cylindrical vessel made of carbon steel with a diameter of 1025 mm and a length of 6 m. The vessel is connected to cryostats of adjacent magnets by means of large bellows (large sleeves) that have lengths of 840 and 1130 mm on the upstream and downstream side of SSS, respectively. The cold magnet, made of steel laminates, is supported inside the cryostat on two GFRE composite support posts spaced by 2.57 meter. One of the composite support is free to move in the longitudinal direction and is also vertically free. The other support is bolted to the cryostat. The three-ply interconnection bellows containing the superconducting bus-bars are welded to the cold mass. The service module of the SSS is connected to the valve box of the cryogenic distribution line through a "jumper connection". The jumper connection consists of an external vacuum jacket and of seven internal pipes that carry cryogens. Each pipeline has one vertical and one horizontal metal hose. The vacuum jacket has one vertical double-gimbal and one horizontal gimbal bellows assembly. Out of the seven internal pipes, only three have significant stiffness and only these three have been modelled. The magnets after being transported to the tunnel are placed in their theoretical position (slots). The interconnect bellows welding and the mounting of jumper and large sleeves are done at this stage. The misalignment of magnets across the interconnection locations is the first reason for relative displacement. A second reason for relative displacement is the fine alignment (smoothing) done after initial cool down to 1.9 K which may cause magnet movements up to ±2 mm. Some areas of the tunnel are prone to ground motion up to 1 mm per year. This displacement is the third reason for relative displacement between cold mass and cryostat.

The objective of the work includes the generation of a user interactive ANSYS input file that can be used even by a non-expert ANSYS user to determine the position of the cold mass in any situation of alignment.

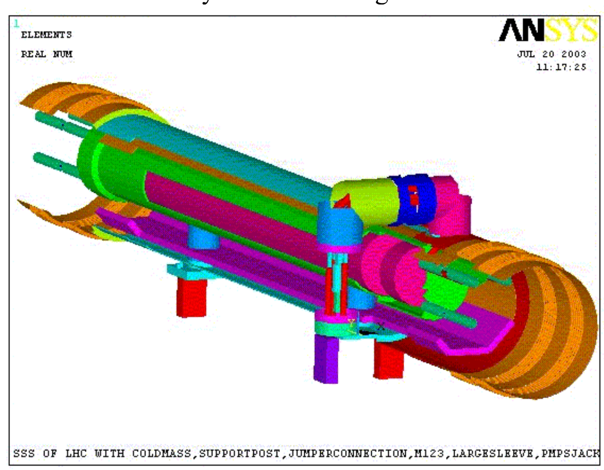

Figure 1: A view of the Short Straight Section (FE model).

MODELING PHILOSOPHY

The corrugated bellows and metallic braided hoses of the internal pipes of the jumper exhibit nonlinear load-displacement characteristics. Since the model is large and contains around 80,000 nodes, it is impractical to use nonlinear static analysis for solution of the problem.

Therefore, a concept of "Multi-Step User-Controlled Linear Static Analysis" was developed. In this approach, approximate secant stiffness(s) are first called into the model by a subroutine for each of the interconnection bellows and metal hoses. The solver calculates the displacements and checks the value of secant stiffness for

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all the bellows and hoses. The secant stiffness is corrected based on the calculated displacement of the bellows and hoses. This iterative process is continued until sufficiently accurate secant stiffness is obtained. This secant stiffness is used for the final solution run.

This special subroutine has been developed by using APDL (ANSYS Programming Development Language). A "LOAD" subroutine has also been developed which takes care of the operating conditions (warm/cold, vacuum/no vacuum) which applies constraint equations for defining kinematics of alignment jack movements and applicable boundary conditions.

This whole process takes around 15 minutes on a Compaq Workstation with single P4 processor with 1 GB RAM.

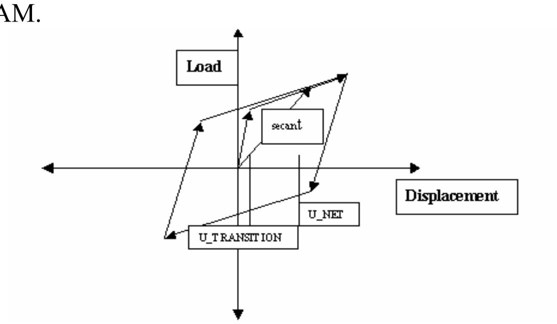

Figure 2: Typical load displacement characteristics, approximated by a bilinear curve.

SELECTION OF ELEMENTS

Table 1: Selection of Elements for the FE Model

Component	Description
Cold Mass	Brick elements for modeling the mass Shell elements for modeling the external shrinking cylinder
Cryostat & Large Sleeves	Shell elements
Cold Supports	Combination of solid, shell and link elements along with constraint equations to model the orthotropic behavior. Constraint equation to model guided longitudinal motion and lifting up situation.
Interconnection Bellows	Beam elements to model the secant stiffness of non-linear load displacement curve.
Metal hoses, double-gimbal & horizontal gimbal bellows assembly of jumper connection	Beam elements and constraint equations to model secant stiffness and hinge friction of non-linear load displacement curve.
Pipe Segments	Beam and pipe Elements
Alignment Jacks	Beam elements with constraint equations

The cryogen distribution line (service module, end of the jumper connection) has been assumed to be fixed. Extremities of large sleeve and interconnection bellows are also assumed to be fixed. Imposed displacements are applied at the location of the alignment jacks to model the alignment process. The free fall condition has been modelled for simulation of ground sinking and imposed displacements have been used to take care of fabrication tolerances on the position of interconnection bellows.

KINEMATIC ARRANGEMENT OF ALIGNMENT JACKS

The SSS is supported on three alignment jacks. The magnet is vertically supported on these jacks with an interface of spherical bearings and it can be moved in the vertical direction by inserting auxiliary jacks. The magnet is aligned in the horizontal plane along two orthogonal degrees of freedom. For each of the jacks, one of the horizontal directions is free and the other one is constrained. Fig. 3 shows position and free direction for each of the jacks.

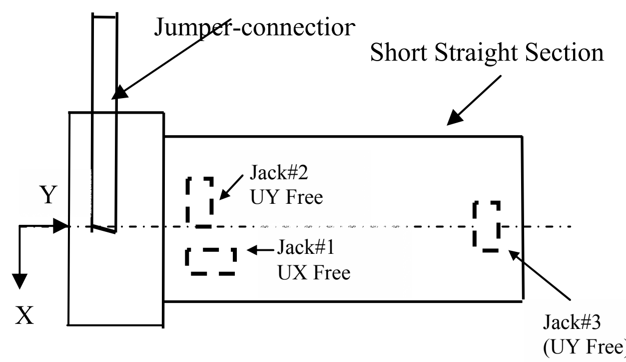

Figure 3: Jack arrangement in upstream configuration.

RESULTS

The analysis shows a relative displacement between the cold mass and the cryostat for all the three displacement conditions. Fig. 5 shows the magnitude of the relative displacement in Z direction when jack # 2 is moved in the vertical downward direction by 0.5, 1.0 and 1.5 mm. Series 1 to 4 are showing displacements at the service module end; series 1 and 2 are for top and bottom points respectively and series 3 and 4 are for +x and –x opposite extremities respectively. Similarly, series 5 to 8 and series 9 to 12 are showing displacements at the other end and mid section of SSS respectively with similar definitions.

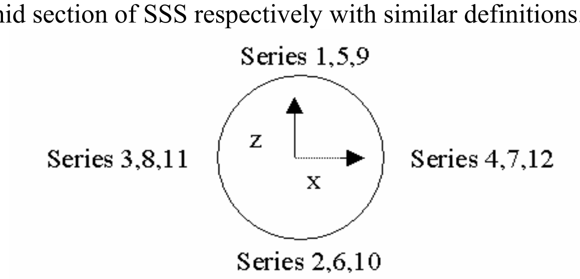

Figure 4: Locations of data points in the series definition.

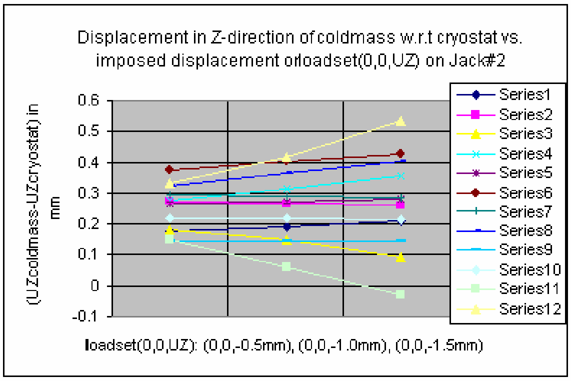

Figure 5: Relative displacement of cold mass in Z: Fig. 6 shows the displacements in X direction for the same load case.

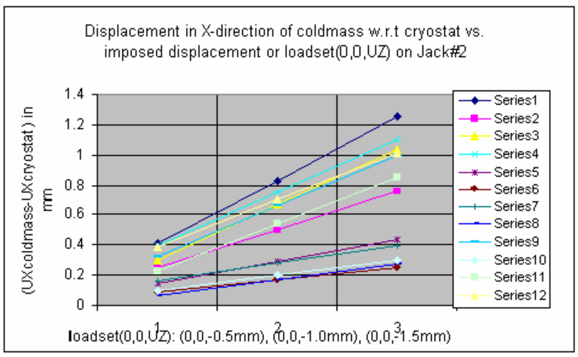

Figure 6: Relative displacement of cold mass in X:

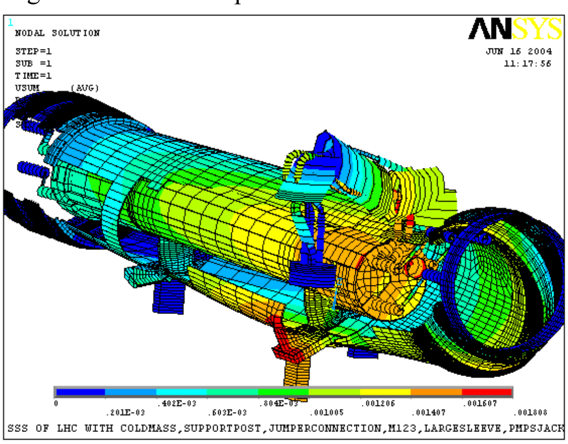

Figure 7: The magnified deformed contour of the SSS components for the induced displacement x = 0, y = 0, z = -1.5 mm on the alignment jack #2 at cold and under vacuum.

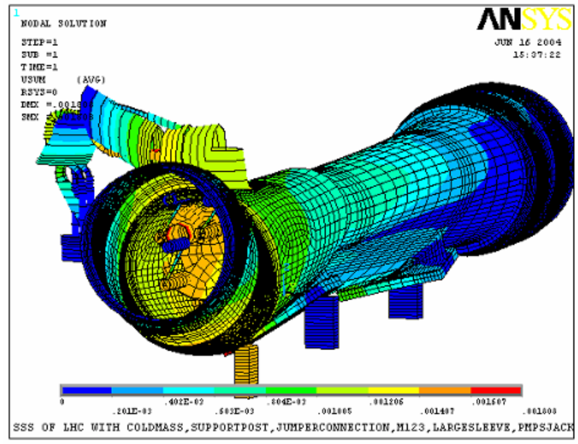

Figure 8–The other side view of the displacement contour of the SSS for the induced displacement case x = 0, y = 0, z = -1.5 mm on the alignment jack #2 at cold and under vacuum.

It can be observed from the results obtained that although the nature of the load-displacements characteristics of bellows and hoses are nonlinear, the relative displacements of the quadrupole cold mass w.r.t. vacuum vessel follow approximately linear patterns with increasing imposed displacements in both directions.

EXPERIMENTAL VALIDATION

The FE model developed will be experimentally validated through a dedicated experiment at CERN (in preparation). An experimental set up has been planned in such a way that individual effects of jumper connection, interconnection bellows and large sleeves can be determined. This will help in detailed and conclusive evaluation of the FE model. The FE model will be tuned according to the results obtained.

FUTURE EXTENSION

Some jumper designs have heights more than 2 meters and they may impose higher reactions on the cryostat and cold mass of the magnet. The same FE model will be used for analysing these situations as well.

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