MECHANICAL COUPLING BETWEEN THE LHC CRYOGENIC DISTRIBUTION LINE AND THE SHORT STRAIGHT SECTION HOUSING THE SUPERCONDUCTING QUADRUPOLE - THEORETICAL ANALYSIS AND EXPERIMENTAL VALIDATION

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Abstract

Liquid and Gaseous Helium are supplied to the superconducting magnets of the Large Hadron Collider (LHC), presently being assembled at CERN, by a cryogenic distribution line (QRL). The cryogenic module of the twin-quadrupole Short Straight Section (SSS) is supplied with these cryogens through a jumper connection linking the service module of the QRL and the SSS. The internal as well as external features of the jumper construction allow for relative displacements between the QRL and SSS with sufficient flexibility to reduce the reaction forces responsible for elastic deformations when the SSS is moved for alignment. The SSS is composed of a cold mass and of a vacuum vessel equipped with fiducials posted on the external vacuum vessel reinforcement rings allowing the precise alignment of the machine when the cryostat is finally closed. A deformation of the structure linking the cold mass and the external vacuum vessel resulting from reaction forces induced by relative displacements of the SSS and the QRL, if unpredictable, would result in an unacceptable misalignment of the quadrupole magnetic axis. A unified FE model was generated at RRCAT to study the elastic behavior of the SSS under the conditions of alignment. This model was validated using a 40 meter long dedicated test setup at CERN. Correlations in the matrix form were generated so that all displacements of the cold mass can be related to the corresponding movements done for alignment. This transfer function, linking the action on the SSS external alignment jacks and the position of the cold mass will be used to properly align the machine in operation.

INTRODUCTION

The SSS can be structurally divided into two main parts: the external cryostat and the internal cold mass of the magnet. The cryostat is an 8 mm thick cylindrical vessel made of carbon steel with a diameter of 1025 mm and a length of 6480 m. Large Sleeves having length of 840 mm and diameter of 1077 mm connect the cryostats of adjacent magnets. Two 'Glass Fibre Reinforced Epoxy (GFRE)' composite support posts, separated by 2.57 m, support the cold mass of the magnet. One of the composite supports is free to move in the longitudinal direction and is also free to move upwards. The other support is bolted to the cryostat. The three-ply magnet-to-magnet interconnection bellows carrying the superconducting bus bars are welded to the cold mass. The service module of the SSS is connected to the distribution line through a "jumper connection". The jumper connection consists of seven (for the Arc) helium carrying internal pipes enveloped by an external vacuum jacket. Each pipeline has one vertical and one horizontal metal hose. The vacuum jacket has one vertical double gimbal universal joint and one horizontal gimbal assembly.

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

- Manufacturing tolerances of in situ welding
- 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 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. The cold mass also deforms when subjected to forces. The magnets after being transported to the tunnel are placed in their theoretical position. The welding of the interconnect bellows and the mounting of jumper and large sleeves are done at this stage. The interconnection bellows may be transversely deformed due to their deviation from the theoretical position in vertical or radial directions thus producing a relative displacement between the cold mass and vacuum vessel. Another reason for relative displacement is the fine alignment (global smoothening) done after initial cool down to 77 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 the cold mass and the cryostat. The knowledge of the absolute position of the cold mass for each jack movement in radial and vertical directions is essential. The maximum relative displacement for satisfactory machine operation is 0.1 mm.

FINITE ELEMENT MODEL

The major components that contribute to the analysis of the structural behaviour are: Cold Mass, Cryostat,

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Jumper-connection, Large Sleeves and Magnet Interconnects.

The mapping of this SSS system behavior (in the simulation) is carried out by developing an application program. The application program has been written within ANSYS using the Ansys Programming Development Language (APDL). This application program includes the experimental hysteresis curves, operational condition specific data like hinge friction and Warm/Normal operating condition of magnet interconnect bellows, constraints of the jacks and free end conditions of the interconnections and large sleeves. The program uses an appropriate stiffness for each flexible members for a given load condition through its logical construction associative paradigm

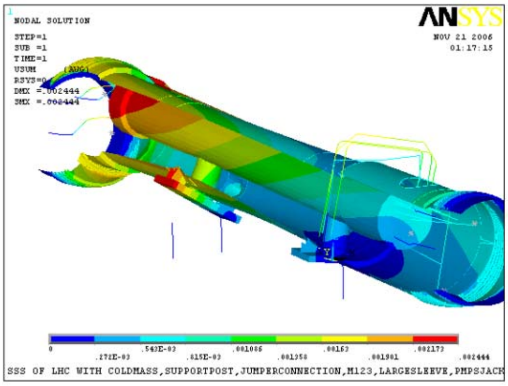

Figure 1: A view of the Short Straight Section Model

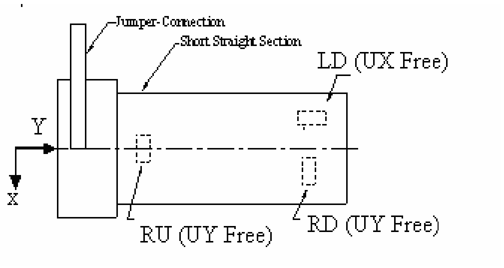

Figure 2: Kinematic arrangement of the jacks of SSS.

EXPERIMENT

An experiment was conducted to validate the unified FE model. . An experimental setup was erected with the help of prototype magnets, cryogenic distribution line and jumper connection,. At both ends of the SSS, the dipole magnets were assembled through the magnet-to-magnet interconnection bellows (M1, M2 and M3) and Large Sleeve. The other extremities of the dipoles was left free to satisfy the actual end condition of the SSS in the LHC ring.

Experiments were done in warm condition without creating vacuum. The erection of the huge experimental set up was planned and accomplished jointly by engineers from CERN, Geneva and RRCAT, Indore, India.

The first stage involved experiments with SSS along with jumper connection but without welding interconnection bellows and without clamping large sleeves at both ends of the SSS. All the measuring instruments and data acquisition system were mounted in this stage itself. The second stage involved experiments with SSS along with jumper connection and interconnection bellows welded at both ends but without clamping large sleeves. The third stage involved experiments with SSS with jumper connection, interconnection bellows welded & large sleeves clamped at both ends.

Figure 3:Experimental set up

FE MODEL TUNING WITH EXPERIMENTAL DATA AND TUNED STIFFNESS

The FE model of the Short Straight section is tuned with the experimented results conducted at CERN by CAT engineers. It was observed that the following stiffness were found to be most important for tuning the FE model:

- Stiffness of the cold mass,
- Stiffness of the column of the support post,
- Vertical and horizontal gimbals, and
- Stiffness of magnet-to-magnet interconnection bellows.

The fixed end conditions of the interconnection bellows were suppressed. Instead, the dipole extremities of the interconnection bellows were prescribed with the observed displacements. The final tuned parameters of the different components of the short straight section are listed in the table-1.

Table-1: Tuned values of important parameters.

Component	Tuned nominal stiffness
Cold mass	Equivalent Young's modulus = $0.61X10^{11}$ N/mm
Cold support post	Equivalent Young's modulus $E=0.24X10^{11}$ N/mm
Vacuum jacket of jumper	Angular stiffness: Bellows of Vertical Gimbal K1=17.8 N-m/grad K2=27.3 N-m/grad Bellow of Horizontal Gimbal K3=74.7N-m/grad
Interconnection bellows	Bending stiffness: 237 N/mm Axial stiffness: 183 N/mm
End conditions of Interconnects	Imposed movement of the dipole's dial readings.

RESULTS

The results are generated for the complete model of the Short Straight Sections in vacuum and normal operating condition. The elastic modulus of steel is increased by 10% for calculation at cold condition. The middle points between the centers of beam pipes on the adjoining faces of the cold mass are taken to demonstrate the result.

The final aim was to establish a relationship between given jack movements and relative displacements of cold mass with respect to cryostat as is given by;

$$\mathbf{d=K\,\Delta}$$

Where Δ, d and K are matrices of jack movements, cold mass absolute movements and proportionality constant respectively.

The first letter of the jack movement gives its jack's orientation, the second letter gives its location and the third letter gives the direction of movement.

The proportionality constants in radial and vertical directions are listed against the jack movement for all type of the movements in tables-2 and 3 for the two points. To get the absolute movement of the result points, the respective proportionality constant needs to be multiplied by the jack movement value.

Table2-Proportionality constant for X-direction (radial)

Jack move ment	Location of the result node	Rigid part (K_{x1})	Flexible part (K_{x2})	*Total* $K_{x1}+Kx_2$
RUX	Upstream	1.272	-0.07	1.202
	Downstream	-0.62	0.14	-0.48
RUZ	Upstream	-0.0346	0.0172	-0.0174
	Downstream	0.0075	-0.0163	-0.0088
RDX	Upstream	-0.2113	-0.0112	-0.2225
	Downstream	1.4705	0.0001	1.4706
RDZ	*Upstream*	0.0000	-0.1722	-0.1722
	Downstream	0.0001	-0.5208	-0.5207
LDZ	*Upstream*	1.1558	-1.108	0.048
	Downstream	1.1557	-0.934	0.222

Table3: Proportionality constant for Z-direction (vertical)

Jack move ment	Location of the result node	Rigid Part (Kz_1)	Flexible Part (Kz_2)	Total $K_{z1}+K_{z2}$
RUX	Upstream	0	-0.0027	-0.0027
	Downstream	0.00013	0.00212	0.00225
RUZ	Upstream	1.1799	0.0535	1.2334
	Downstream	-0.4954	-0.0002	-0.4956
RDX	Upstream	0.0001	0.0009	0.0010
	Downstream	-0.0004	-0.0015	-0.0019
RDZ	Upstream	1.2915	-1.3515	-0.0603
	Downstream	-0.6341	1.0108	0.3767
LDZ	Upstream	-0.1378	0.1066	-0.0312
	Downstream	0.8048	-0.616	0.1886

CONCLUSION

The experimental observations were sufficient to tune the unified FE Model of SSS. Although, the role of vacuum in the cryostat and the jumper have not been experimentally determined, the FE model has been tuned for warm and no vacuum condition and was extrapolated to predict coupling in cold and vacuum conditions.

The model is tuned within an accuracy of ±0.15 mm.

Table-4 summarises out the behaviour of elastic coupling in case of all five-jack movements.

Table-5 shows the displacements of both ends of the cold mass for 1mm movement of RU, LD and RD jack in radial and transverse direction.

Table-4.Behavior of the Elastic Coupling with respect to the rigid body displacements.

Jack move -ment	Location	Displacement in radial direction (x-direction)	Displacement in vertical direction (z-direction)
RuX	Upstream	REDUCTIVE	ADDITIVE
	Downstream	REDUCTIVE	ADDITIVE
RuZ	Upstream	REDUCTIVE	ADDITIVE
	Downstream	REDUCTIVE	ADDITIVE
RDX	Upstream	ADDITIVE	ADDITIVE
	Downstream	ADDITIVE	ADDITIVE
RDZ	Upstream	REDUCTIVE	REDUCTIVE
	Downstream	REDUCTIVE	REDUCTIVE
LDZ	Upstream	REDUCTIVE	REDUCTIVE
	Downstream	REDUCTIVE	REDUCTIVE

Table-5. The displacement of the beam pipe for 1mm movement of the jacks in transverse and radial direction.

Jack movement	Location	Displacement (in mm) in radial(x) and transverse(Z) direction	
		X	Z
1mm in RUX direction	Upstream	1.202	-0.003
	Downstream	0.048	0.002
1mm in RUZ direction	Upstream	0.017	1.23
	Downstream	0.009	-0.50
1mm in RDX direction	Upstream	-0.222	0.002
	Downstream	1.47	-0.060
1mm in RDZ direction	*Upstream*	-0.172	-0.06
	Downstream	-0.521	0.377
1mm in LDZ direction	Upstream	0.048	-0.031
	Downstream	0.222	0.189

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