MODELING OF THE RF-SHIELD SLIDING CONTACT FINGERS FOR THE LHC CRYOGENIC BEAM VACUUM INTERCONNECTS USING IMPLICIT AND EXPLICIT FINITE ELEMENT FORMULATIONS

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Abstract

The short interconnect length between the LHC superconducting magnets required the development of an optimised RF shielded bellows module, with a low impedance combined with compensation for large thermal displacements and alignment lateral offsets. Each bellows is shielded by slender copper-beryllium fingers working as pre-loaded beams in order to provide a constant force at the sliding contact. Unless the sliding friction and some geometrical parameters of the fingers are kept within a limited range, a large irreversible lateral deflection towards the vacuum chamber axis may occur and eventually block the beam aperture. The finite element analysis presented here simulates this failure mechanism, providing a complete understanding of the finger behaviour as well as the influence of the various design parameters. An implicit non-linear two-dimensional model integrating friction on the sliding contacts, geometrical non-linearity and plasticity was implemented in a first stage. The design was then verified through the whole working range using an explicit formulation, which overcame the instabilities resulting from the sudden release of internal energy stored in the finger.

INTRODUCTION

The 27 km long LHC particle accelerator required the development of superconducting magnet interconnect components, which had to be designed according to a set of stringent specifications [1]. Among these components, are the interconnect plug-in modules (PIM), installed in the machine as a pre-assembled module, comprising an expansion joint and an RF-bridge shielding, which compensates for the magnets thermal displacements and ensure electrical continuity. In a typical arc interconnect with a 50 mm diameter beam vacuum chamber, the RF-bridge is composed of 30 fingers, about 100 mm long, which work as spring loaded cantilevered beams in order to provide the minimum contact force required to achieve a total interconnect resistance under 100 µΩ at operating conditions. Additionally, the design thickness of 0.3 mm and width 3.6 mm, material properties and finger shape had to be chosen in order to prevent the collapse of the finger during the compression stroke seen by the PIM during the warm-up of the magnets. After the design validation through prototypes and a test campaign on the full-scale magnet String II [2], a total of 3800 units were fabricated and delivered at CERN as ready to install assemblies.

With the interconnect installation still on-going, the first sector to be completed had to be warm-up for consolidation work after a first cool-down. Unexpectedly,

six PIM units, out of the 382 in that arc, where found with some fingers plastically deformed into the beam aperture. Although a mechanical analysis had been performed during the design phase [3], an in-depth analysis based on more detailed models was found necessary in order to fully characterise the failure mechanisms involved and assess the influence of each design parameter.
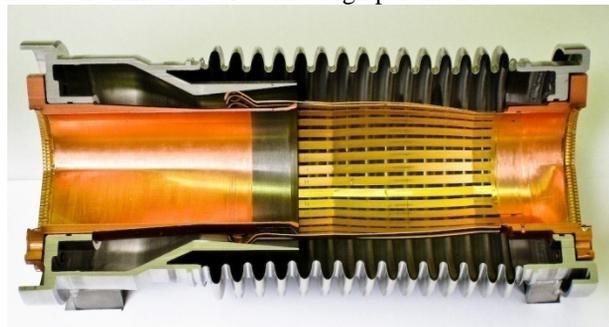

Figure 1-Section of a plug-in module showing the contact fingers and guiding tubes forming the RF-bridge.

Figure 2 – Main geometrical parameters of the contact finger characterising its shape before assembly.

The fingers are made of copper beryllium C17410 TH02 sheet, cut by wire electro-erosion, cold formed to a specific shape (Figure 2) and finally laser welded to a copper transition piece. A 5 µm gold coating, deposited by electroplating, provides a low resistance at the contact with the inner copper transition tube. The latest is coated with a 3 µm thick rhodium layer in order to prevent cold welding in ultra-high vacuum. The contact force is ensured by a second contact at the tip of the finger, against a stainless steel guiding conical tube. The 6º angle of this cone was set to provide a nearly constant contact force at the Rh-Au contact over the working range of the PIM.

During the magnet warm-up stroke, the finger is subjected to an axial compression load that results from the friction at the two contacts, finger/inner tube (Au/Rh) and finger/outer tube (Au/316LN) plus a bending moment with magnitudes depending on the relative position of the contact points. Being under compression, the stability of the finger is largely influenced by the distance between the Au/Rh contact and the extremity welded to the copper transition, defined as span (S). The span at cold depends on the lengths of the interconnected magnets, mechanical

tolerances and temperature differences during cool-down or warm-up.

IMPLICIT NON-LINEAR 2D ANALYSIS

A system composed by the finger, the contact with the inner copper tube and the contact with the outer guiding stainless steel cone was implemented in ANSYS finite element code [4].The finger was modelled with uniaxial, two node, beam elements with capability to model material plasticity. The 2D model representing the structure was loaded through a command text file written in order to be fully parametric. As such, the finger geometry, material properties and real constants could be easily made to vary either by changing the parameters in the input file manually, or using ANSYS programming language. The contacts were implemented with surface elements based on the augmented Lagrangian algorithm. Both contact surfaces with the copper and stainless steel parts were modelled as rigid surfaces. A circle of radius 0.5 mm models the contact point with the inner tube, and a straight line with the same inclination as the cone simulates the outer guiding tube at the region of interest. An elasto-plastic bilinear model was used to model the finger material properties at cold. Tensile tests at 4.2 K resulted in a Young modulus of 154 GPa, yield stress 749 MPa and a plastic modulus of 574 MPa [5]. Non-linear behaviour resulting from large displacements where also taken into account.

As compression of the PIM starts with the contact fingers already pre-stressed, two load steps where necessary. In the first load step, the finger is bent from its initial shape by moving the cone surface from a fictive upper position towards the finger. During this process, the finger is pushed by the cone surface against the contact point representing the inner tube. At the end of this load step the finger is in a load state equivalent to the cold working position in the machine. The second load step simulates the magnets warm-up, which is seen by the PIM as a compression stroke, through an imposed displacement applied at the welded extremity of the finger.

Static friction between clean surfaces in vacuum is high and, therefore, plays a major role in the behaviour of the finger. Both contacts were modelled to include Coulomb's friction. One of the challenges of this simulation was the numerical instabilities induced by the sliding contacts, which difficult the convergence of the Newton-Raphson algorithm used in the code. In order to help the convergence, a small pressure, equivalent to less than two orders of magnitude lower than the actual contact force, was applied on the opposite face of the finger to prevent chattering due to numerical instabilities.

Although the friction coefficients of the two contacts are different, their values could not be determined independently. A single friction coefficient was used in both, which can be seen as an equivalent value that would result in the same compression force in the finger between the Au/Rh contact point and the welded extremity. As the plastic deformations occur only in this region, the approximation of the two friction coefficients by an equivalent value can be assumed to have negligible influence on the final results.

Pin on disc tribological tests in vacuum and at 100K for the Au/Rh pair gave dynamic friction coefficients between 1.0 and 1.4 [6]. However, the geometry of the contact and the velocity was not representative of the real conditions. A series of tests on real PIM's at 15 K and UHV conditions allowed to measure the axial total force on the 30 fingers as a function of the displacement along the complete stroke [7]. The results obtained allowed to determine an equivalent friction coefficient that is representative of the real surface and geometrical conditions. Running the finite element model iteratively for various friction coefficients, it was possible to find a value for which the axial force matches the results of the tests. Figure 3 shows the measured forces, starting the movement from different points in the stroke, compared with the force predicted by the model over the full stroke. A value of 0.4 was taken as the equivalent friction coefficient.
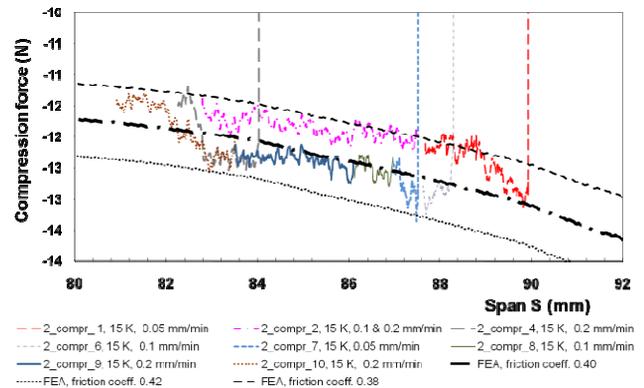

Figure 3- Compression force measured during friction tests [7] compared to the FEA model results. A friction coefficient of 0.40 correlates well with the experimental data.

The same model was then used to analyse the influence of the various design parameters on the finger behaviour during the PIM compression. As the PIM's found damaged in the machine presented non-conformities in the geometry, their influence was investigated. The specification for the second bending angle (A2) was 12º and the height at the tip (h) 6.7 mm. Figure 4 compares the deformed shape of a conforming finger with that of one PIM with A2= 45º and h= 3.4 mm, found damaged after the first warm-up. Whilst the conforming finger slides between the outer and inner tubes as expected, in the non-conforming geometry case, a plastic hinge is created near the contact with the inner tube from the beginning of the displacement, leading to collapse towards the beam axis. The results also showed that this collapse only occurs if the initial span is long (typically more than 84 mm), which was the case of the damaged PIM's.
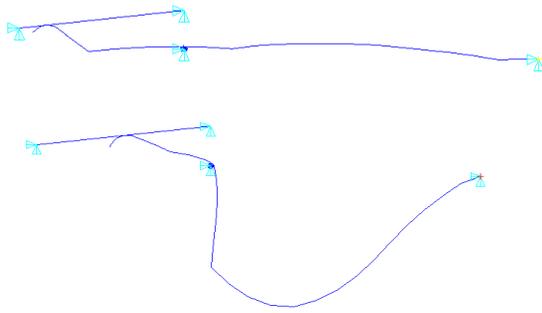
Figure 4 – Deformed finger with nominal geometry (top) during the machine warm-up. Simulation result for a non-conforming geometry corresponding to a PIM found damaged after the first LHC sector warm-up (bottom).
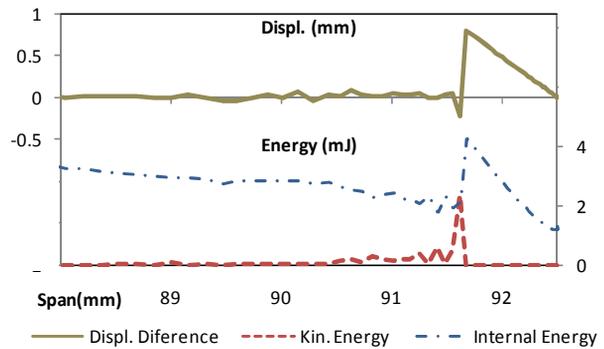

Figure 5 – Difference in axial displacement between the welded end and the tip of the finger (top) as a function of the span during a compression stroke, for a friction coefficient of 2.0. Internal and kinetic energy (bottom).

VERIFICATION WITH AN EXPLICIT FORMULATION

Given the consequences of a finger failure to the machine operation, the design must have a large margin of safety for all parameter variations, including friction. The implicit model could simulate the finger behaviour for friction values around those measured in the tests, but it showed its limitations when the friction was increased. For hypothetical high values of friction coefficient, for example due to defects in the surface coatings, the finger may become trapped between the two contacts and not slide immediately as the PIM compression starts. During this process the finger is subjected to an increasing bending moment, storing internal energy. As the compression continues, the geometry of the finger makes that this bending is in a direction that gradually reduces the contact normal forces, until the point when the friction can no longer balance the reaction forces. The internal energy is then rapidly released with a fast movement of the finger tip. This point in a force-displacement curve corresponds to a zero derivative that cannot be overcome by the Newton-Raphson solver of an implicit formulation. In order to fully demonstrate the design tolerance to high friction, the explicit code from ABAQUS [8] was used to perform a dynamic analysis on the baseline finger design, with a friction coefficient of 2.0. Since the real PIM compression process is quasi-static through most of the stroke, the analysis time of the corresponding load step had to be much lower than the period of the first natural mode of the finger (aproximately 0.06 s), such that artificial dynamic effects do not compromise the results. The time intervals were 0.05 s and 1 s in the first and second steps, respectively.

The results are presented in Figure 5. The top graph shows the difference between the movement of the tip and the compression stroke. The finger is initially blocked and stores internal energy, but once the friction forces become lower than the sliding threshold, that energy is suddenly released in the form of kinetic energy. From that point on, the finger slides as expected. The maximum equivalent stress was 370 MPa, well below the elastic limit.

CONCLUSIONS

A detailed analysis of the contact fingers, simulating the quasi-static sliding friction and non-linear material behaviour, allowed to acquire an in-depth understanding of the mechanisms that may lead to failure of the PIM RF bridge during magnet warm-up. It was shown that the failures occurred in the LHC were due to a manufacturing non-conformity on the geometry. The combination of results from the implicit and explicit models allowed to conclude that the initial baseline design is not only compatible with all the requirements, but also has a large safety margin against finger collapse. Failure only occurs for largely out-of tolerance fingers installed between magnets in configurations that have large finger spans at cold. The explicit model also allowed the simulation of the finger behaviour throughout the full compression stroke with high friction, proving that the design is safe even if, for uncontrolled reasons, the friction in some fingers is much higher than expected.

ACKNOWLEDGMENTS

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T28 Subsystems, Technology and Components, Other