POSSIBLE MOVEMENTS OF THE MILAN SUPERCONDUCTING COILS UNDER THE INFLUENCE OF MECHANICAL STRESSES.

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SUMMARY

The cryostat and the superconducting coils when the latter are axially prestressed and subjected to large radial magnetic forces, can undergo a process of "stick and slip" very dangerous for the superconductor stability.

This paper presents the theoretical models used at the Milan Laboratory to determine the characteristics of the coils motion and to estimate the effects in the coils during the slipping.

The case of the superconducting coils of the Milan Cyclotron project and the means adopted in order to minimize such effects are discussed.

INTRODUCTION

In the Milan superconducting coils design[1-3] the dynamical interaction between the coils and the helium vessel during the magnet excitation acquires a large importance as a consequence of the intense axial prestressing forces exerted on the coils.

When the field is turned on, the coils increase radially and trail the vessel until the frictional forces are greater than the elastic forces produced by the vessel deformations. As soon as the relative equilibrium between the coils and the vessel is broken, these undergo sudden and opposite movements.

This "stick and slip" process repeats itself for different current levels in the coils and can produce the transition to the normal state of the superconducting cable through a temperature increase of the copper matrix or generation of high induced currents in the superconducting filaments.

The conditions for the relative equilibrium and motion of the coils-vessel system, the main features of these movements, their thermal and electrical effects on the superconducting cable and the mechanical solution adopted for the coils design in the Milan project are the subjects of this paper.

DYNAMIC BEHAVIOUR OF THE COILS-VESSEL SYSTEM

To study the dynamics of the coils-vessel system we assume these elements are made by elastic cylindrical rings. The Fig. 1 shows a vertical section of the system and the linear specific forces diagram for an elemental sector at the equilibrium condition: $F(I)$ represents the radial component of the linear magnetic force acting on the coils at the current I, $\Phi(I)$ the linear axial force (sum of the linear prestressing force and the axial component of the linear magnetic force), $\mu\,\Phi(I)$ the linear frictional force, $-k_1x_1$ and $-k_2x_2$ the linear elastic forces arising from the action of the remaining parts of the system on the considered elemental sector. The elastic force coefficients are given by:

$$k = ES/R^2 \tag{1}$$

where E, S and R are respectively the Young modulus, the section area and the mean radius of the corresponding element. For the quantities x_1 and x_2 we will use the following notations:

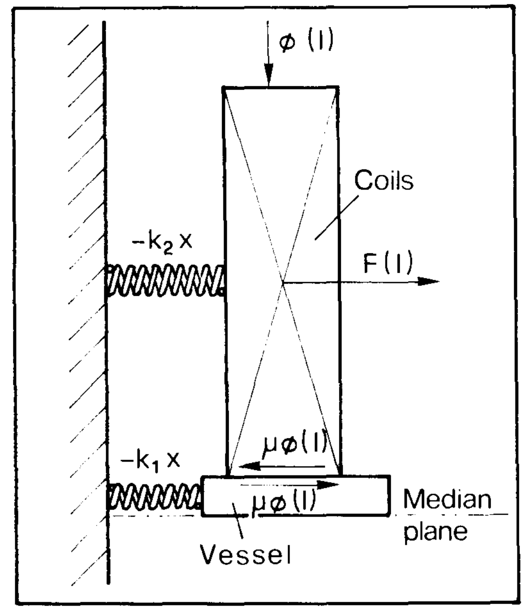

Fig. 1 - Sketch of the coils-vessel system and diagram of the linear specific forces.

$x_1(I,0)$, $x_2(I,0)$ are the deformations undergone at the current I by the vessel and by the coils when they behave as a compact body,

$x_1(I_o,t)$, $x_2(I_o,t)$ are the time dependent deformations which take place at the current $I = I_o$ during the slipping.

The condition for the relative equilibrium of the two elements is given by the system:

$$\begin{aligned} &F(I) - k_2x_2(I,0) - \mu\,\Phi(I) = 0 \\ &-k_1x_1(I,0) + \mu\,\Phi(I) = 0 \end{aligned} \tag{2}$$

Considering that the coils and the vessel, as long as they make a compact body, undergo the same deformation $x(I,0) = x_1(I,0)-x_1(0,0) = x_2(I,0)-x_2(0,0)$ where $x_1(0,0)$ and $x_2(0,0)$ are the initial deformations, the system (2) becomes:

$$\begin{aligned} &F(I) - k_2x(I,0) - k_2x_2(0,0) - \mu\,\Phi(I) = 0 \\ &-k_1x(I,0) - k_1x_1(0,0) + \mu\,\Phi(I) = 0 \end{aligned} \tag{3}$$

The initial deformations $x_1(0,0)$ and $x_2(0,0)$ arise as a consequence of the prestressing force and the differential contraction of the two elements during the cool down.

The solution of the system (3), when the term μ is lower than the static frictional coefficient μ_s, is given by the following expressions:

$$x_1(I,0) = \frac{F(I)}{k_1+k_2} + \frac{k_2}{k_1+k_2}\,(x_1(0,0) - x_2(0,0)) \qquad (4)$$

$$x_2(I,0) = \frac{F(I)}{k_1+k_2} + \frac{k_1}{k_1+k_2}\,(x_2(0,0) - x_1(0,0)) \qquad (5)$$

$$\mu = \frac{k_1}{k_1+k_2}\;\frac{F(I) - k_2(x_2(0,0) - x_1(0,0))}{\Phi(I)} \qquad (6)$$

When at the current $I = I_o$ the condition $\mu < \mu_s$ is not fulfilled, the coils and the vessel begin to slip. The motion of the two elements is determined, until the relative speed does not change its sign, by the equations:

$$F(I_o) - k_2x_2(I_o,t) - \mu_d\,\Phi(I_o) + \text{further damping terms} = m_2\,\ddot{x}_2(I_o,t)$$

$$- k_1x_1(I_o,t) + \mu_d\,\Phi(I_o) + \text{further damping terms} = m_1\,\ddot{x}_1(I_o,t) \qquad (7)$$

where m_1 and m_2 are the elemental sector masses and μ_d the dynamic frictional coefficient.

Neglecting in (7) the further damping terms we obtain that the two elements perform an harmonic motion described by:

$$x_1(I_o,t) = x_1(I_o,0)\left(\left(1-\frac{\mu_d}{\mu_s}\right)\cos 2\pi\frac{t}{\tau_1} + \frac{\mu_d}{\mu_s}\right) \qquad (8)$$

$$x_2(I_o,t) = x_2(I_o,0) + \frac{k_1}{k_2}\,x_1(I_o,0)\left(1 - \frac{\mu_d}{\mu_s}\right)\left(1 - \cos 2\pi\frac{t}{\tau_2}\right) \qquad (9)$$

where:

$$\tau_1 = 2\pi R_1(\delta_1/E_1)^{\frac{1}{2}} \qquad \tau_2 = 2\pi R_2(\delta_2/R_2)^{\frac{1}{2}} \qquad (10)$$

are the motion periods, being δ_1 and δ_2 the mean densities of the two elements.

The motion keeps till the instant $t = t_o$ in which the relative speed of the coils and the vessel becomes nul: since this moment the two elements are again a compact system which undergoes damped oscillations. The positions reached by the vessel and the coils at the end of the damped oscillations ($t = \infty$) are given by:

$$x_1(I_o,\infty) = x_1(I_o,t_o) + x(I_o,\infty) \qquad (11)$$

$$x_2(I_o,\infty) = x_2(I_o,t_o) + x(I_o,\infty) \qquad (12)$$

where:

$$x(I_o,\infty) = \frac{F(I_o) - k_1x_1(I_o,t_o) - k_2x_2(I_o,t_o)}{k_1+k_2} \qquad (13)$$

For $I > I_o$ the new conditions of the relative equilibrium are expressed by the following equations:

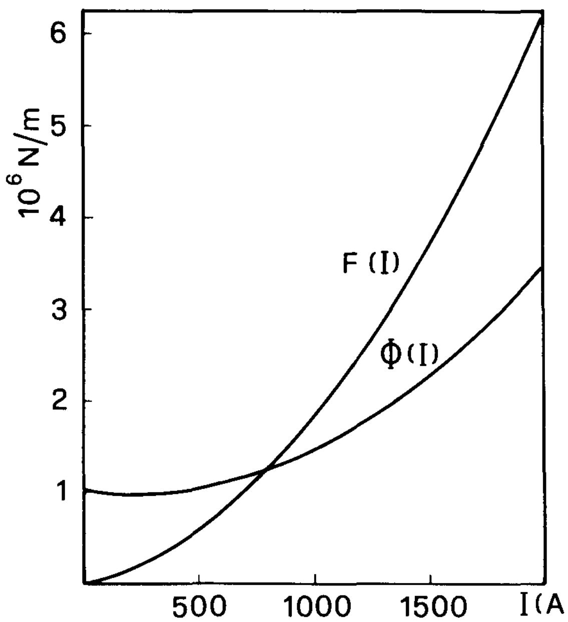

Fig. 2 - Radial and axial linear forces acting on the Milan coils sector as a function of the excitation current.

$$F(I) - k_2x(I,0) - k_2x_2(I_o,\infty) - \mu\,\Phi(I) = 0$$

$$- k_1x(I,0) - k_1x_1(I_o,\infty) + \mu\,\Phi(I) = 0 \qquad (14)$$

where:

$$x(I,0) = x_2(I,0) - x_2(I_o,\infty) = x_1(I,0) - x_1(I_o,\infty)$$

The system (14) is exactly alike the system (3), this means that the coils and vessel slipping reproduces periodically with the same features above-described.

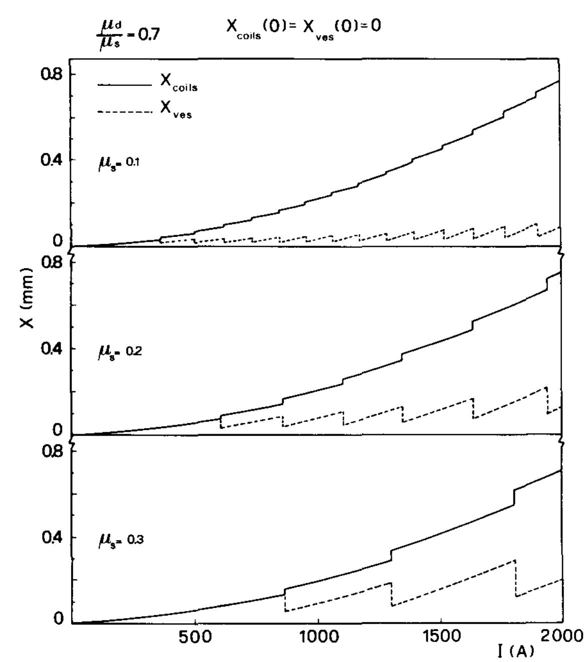

Fig. 3 - Deformations and slipping jumps of the coils and the vessel as a function of the current and the static frictional coefficient.

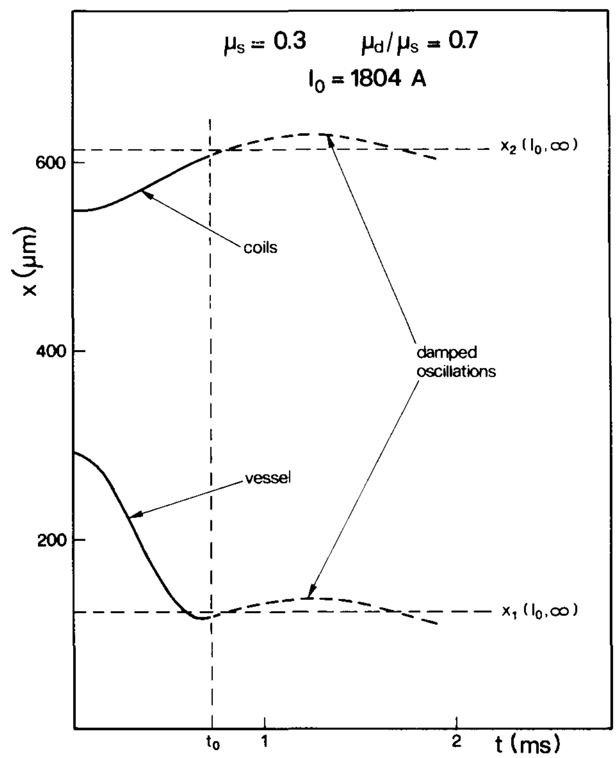

Fig. 4 - Typical oscillations of the coils and the vessel during the slipping.

This mechanical behaviour in the case of the Milan superconducting coils and the helium vessel is summarized in the following figures. The Fig. 2 shows the radial and axial linear forces acting on the coils as a function of the exciting current: in particular the initial value $\Phi(0) = 1.01\ 10^6$ N/m corresponds to the 700 tons prestressing force foreseen in the coils design[2].

The deformations and the slipping jumps undergone by the coils and the helium vessel for different μ_s values are reported in Fig. 3: these data have been obtained for $\mu_d/\mu_s = 0.7$ and assuming $x_1(0,0)=x_2(0,0)=0$.

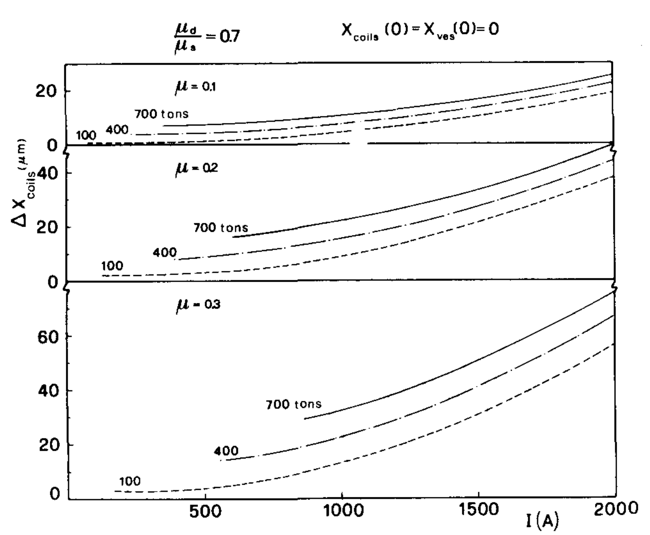

Fig. 5 - Amplitudes of the slipping deformations as a function of the current and prestressing force for different values of the static frictional coefficient.

The Fig. 4 shows the oscillations of the coils and the vessel for a prestressing force of 700 tons and $\mu_s = 0.3$, when the coils current is $I_o = 1804$ A (corresponding to the third jump shown in Fig. 3).

The slipping deformations increase with the coils current and the prestressing force as shown in Fig. 5: in this figure the discrete data have been represented by continous curves to make easier the comparison of the results.

EFFECTS OF THE DEFORMATIONS AND SLIPPING

The effects of the deformations on the coils have been already examined and reported elsewhere[2].

The radial deformation of the helium vessel gives rise to a tensile stress which, for $\mu_s = 0.3$ (and $\mu_d/\mu_s = 0.7$), amounts approximately at 8 kg/mm^2. For the vessel design this stress level is too high because it is added to already high stresses arising by axial magnetic forces: then it is necessary to keep the vessel deformations within about 0.1 mm.

The slipping is essentially dangerous for the coils operation in consequence of the high currents induced in the superconducting filaments and mechanical dissipative processes.

The slipping motion gives rise to an induced current in the whole coils whose intensity can be expressed by:

$$I_{ind}(t) = -B_{iron}\frac{2\pi R_2 N}{L} X \cos 2\pi \frac{t}{\tau_2} \tag{15}$$

where B_{iron} is the mean magnetic field produced by the poles and the yoke in the coils region, N, L and X are respectively the turns number, the inductance and the oscillations amplitude of the coils.

Considering that the slipping movements of the coils occur almost fully during the first stage ($t < t_o$) we can assume:

$$X = \frac{k_1}{k_2} x_1(I_o,0)\left(1 - \frac{\mu_d}{\mu_s}\right) \tag{16}$$

The maximum induced current is very low, typically a few tens of mA, but its time derivative is high, producing a rapid variation of the magnetic field given by:

$$\frac{dB}{dt} = \alpha \frac{dI_{ind}}{dt} =$$

$$= \alpha B_{iron}\frac{(2\pi)^2 R_2 N}{L\tau_2} X \sin 2\pi\frac{t}{\tau_2} \tag{17}$$

The time variation of the magnetic field induces in the superconducting filaments the current density[4]:

$$J_s = \frac{l^2\, dB/dt}{\pi^2 \varrho\, d_s} \tag{18}$$

where l is the half length of twisting, ϱ the matrix resistivity and d_s the mean diameter of the filaments.

The induced current is a shielding current and flows in opposite directions in each half of the filaments, then its intensity is:

$$I_s = \mp J_s A_s/2 \tag{19}$$

where A_s is the superconductor section.

The current I_s needs not to exceed the difference between the critical current I_c and the operating coils current I, therefore to avoid a transition from the superconducting to the normal state, the coils oscillation amplitude X must be limited to:

$$X < \frac{(I_c - I)\,\varrho\, d_s\, L\, \tau_2}{\alpha\, l^2\, B_{iron}\, R_2\, N\, A_s} \qquad (20)$$

Considering the following data:

$\varrho = 3\ 10^{-10}\ \Omega m$ $\quad d_s = 70\ 10^{-6}\ m$ $\quad A_s = 2.1\ 10^{-6}\ m^2$

$R_2 = 1.08\ m$ $\quad N = 3.3\ 10^3$ $\quad L = 20\ H$

$\alpha = 2.2\ 10^{-3}\ T/A$ $\quad B_{iron} = 0.5\ T$

$I_c = 2700\ A\ (B=5\ T)$ $\quad \tau_2 = 1.85\ 10^{-3}\ s$

we obtain for the maximum operating current (I = 1944 A) in the Milan coils:

$$X < 45\ 10^{-6}\ m$$

and this result corroborates the necessity to reduce the coils displacements during the slippling.

As regards the mechanical dissipative effects we consider only those arising by the friction between the coils and the vessel. As this process occurs in short time (typically a few milliseconds) we can assume there is not a thermal exchange with the helium bath and the energy released increases the matrix enthalpy.

For the slipping occurring at the current I_o, supposing the energy is fully released in the first pancake, the specific enthalpy increase of the matrix is given by:

$$\frac{\Delta H}{m} = \mu_d\, \Phi(I_o)\,(x_2(I_o,t_o) - x_1(I_o,t_o) - x_2(I_o,0) + x_1(I_o,0))/\,n\,s\,\delta \qquad (21)$$

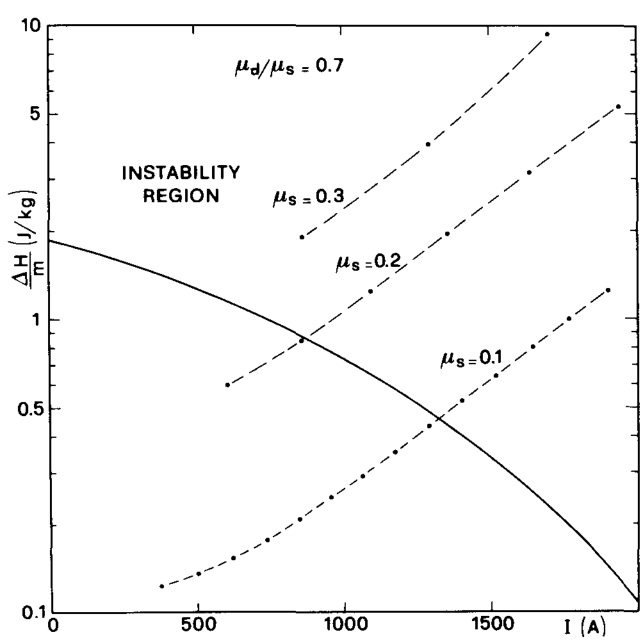

Fig. 6 – Specific enthalpy increase of the copper matrix in the Milan coils produced by the friction (dashed lines) and maximum specific enthalpy increase supported by the superconducting cable (solid line).

where n is the turns number of the pancake, s and δ the section and density of the matrix.

The Fig. 6 shows the specific enthalpy increase of the copper matrix for different values of μ_s as a function of the exciting current in the coils. In the same figure we have reported the maximum specific enthalpy increase supported by the superconducting cable before its temperature exceeds the critical one.

From these data we can conclude that is impossible reach the maximum current in the coils also with low values of μ_s if the first pancake surface is directly involved in the frictional movements.

As the Milan coils are separated from the vessel by fiberglass G11 sectors (2.5 mm thick) we have checked which of the two frictional coefficient (stainless-steel - G11 or G11 - tinned copper) is lower. The measurements made in the pressure range of 200 - 500 bar have indicated that the tinned copper slides on the G11 easier than the stainless steel; if between the stainless steel and G11 is interposed a teflon sheet, the situation is reversed.

For these reasons we decided to interpose two teflon sheets, 0.2 mm thick, between the vessel base and the coils and between the coils and the prestressing flange.

Since the Milan superconducting coils are splitted in two sections[2] which can excited oppositely, sliding movements can occur also between the two sections. Therefore we decided to interpose a teflon sheet also between the G11 sectors separating the two sections.

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