THE NUMERICAL SIMULATION OF REINFORCED HIGH MAGNETIC FIELD COIL

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Abstract: The performance of a 40 T pulsed magnet is simulated with finite element method. ANSYS software for numerical simulation of magnetic field and mechanical deformation in pulsed magnet was applied. Due to construction symmetry the 2-D model of multilayer reinforced pulsed magnet was realized. The coil was wound with standard copper wire. The results show that the finite element technique is useful tool for the design of pulsed coil. Analysing the distribution of magnetic forces and layers displacement it was found that high mechanical overloads took place in copper winding but magnet construction had an acceptable mechanical stability due to interlayer reinforcement. Key words: pulsed magnet, numerical simulation.

1. INTRODUCTION

High magnetic field is an important tool, which can be used in a wide variety of scientific and technological areas. Materials used in high magnetic field coil have to be loaded to their mechanical and thermal limits. However, the number of operation cycles of pulsed magnet sharply decreases with the increase of magnetic field value and it is limited by mechanical and thermal overloads in pulsed magnet construction.

The design of pulsed magnets involves the calculation of pulse shape, magnetic forces and absolute deformations. The design process is aimed at the optimization of performance with respect to the desired characteristics of pulsed field and pulsed magnet construction rigidity and durability [1]. For magnetic field intensity, magnetic flux density and absolute values of displacement calculation recently used a finite elements technique. The commercially available software package ANSYS included the electromagnetic field and structural analysis is one of the most powerful tools and it can be used for coils optimization.

For numerical simulation of pulsed magnets and structural analysis are coupled via electromagnetic force. Electromagnetic field analysis has a strong influence on the structural analysis. Therefore these are solved simultaneously by a so-called coupled field analysis. In this paper the numerical analysis of magnetic field and deformations took place in pulsed coil due to Lorentz forces is described.

2. OBJECT OF STUDY

The ideal conductor for pulsed coil ought to combine the high mechanical strength with high electrical conductivity. But in practice the high conductivity typically is combined with the low mechanical strength of material. The soft copper is good conductor but the tensile strength of cooper is of the order 0.25 GPa and it corresponds to peak field of the order 25 T [1]. At magnetic field of 50 T a load of the order of 1 GPa acts on the inductor construction and traditional materials are inapplicable without the special reinforcement [3-6]. The mechanical strength of the inductor
construction can be increased using modern glass fibre, carbon-epoxy composites [7] or poly p-phenylene benzo-bisoxazole-epoxy composites [8] for coil reinforcement. The application of new composite materials in pulsed magnetic field inductor design has provided the development of non-destructive magnets in 40–60 T range [9].

In our case the multilayer construction of cooper wire wound coil reinforced with glass fibre-epoxy composite is analyzed. The inductor geometry was verified analytically to find the maximal available value of magnetic field (see Figure 1).

Fig. 1. Peak field dependence on the coil geometry at liquid nitrogen temperature

### 3. SIMULATION METHODOLOGY

Due to construction symmetry the simplified 2-D structure is modelled. The PLANE 13 4-node (2-D coupled field solid) elements in ANSYS for modelling of the multiplayer reinforced solenoid are used. The solenoid consists of 108 copper wire turns fixed in common epoxy structure with glass fibre reinforcement and stainless steel shell (see Figure 2). The details of coil geometry, current density in adequate coil and materials properties are given in Table 1–2. The basic equations and computing details are already explained in many scientific works [10].

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Copper wire wound coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore radius</td>
<td>4</td>
</tr>
<tr>
<td>Layers</td>
<td>6</td>
</tr>
<tr>
<td>Turns/layer</td>
<td>18</td>
</tr>
<tr>
<td>Ratio of outer and inner diameter $\alpha$</td>
<td>3.4</td>
</tr>
<tr>
<td>Ratio of height to inner diameter $\beta$</td>
<td>3</td>
</tr>
<tr>
<td>Cross section of wire</td>
<td>$\varnothing$ 1.5 mm</td>
</tr>
<tr>
<td>Thickness of stainless steel shell</td>
<td>15 mm</td>
</tr>
<tr>
<td>Current density in coil $j$, A/m$^2$</td>
<td>0.561 e10$^10$</td>
</tr>
<tr>
<td>Magnetic permeability of materials and liquid nitrogen outside coil $\mu$</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 1. Basic parameters of analyzed coil

<table>
<thead>
<tr>
<th>Material</th>
<th>Young's modulus $E$, GPa</th>
<th>Density, $\rho$, kg/m$^3$</th>
<th>Yield strength, $R_{0.2}$, MPa</th>
<th>Tensile strength, $R_m$, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu wire</td>
<td>110</td>
<td>8900</td>
<td>250</td>
<td>320</td>
</tr>
<tr>
<td>Glass fibre</td>
<td>85</td>
<td>2540</td>
<td>3200</td>
<td>4500</td>
</tr>
<tr>
<td>Epoxy resin</td>
<td>3</td>
<td>1200</td>
<td>42</td>
<td>70</td>
</tr>
<tr>
<td>Plastic body</td>
<td>30</td>
<td>1300</td>
<td>115</td>
<td>168</td>
</tr>
<tr>
<td>Steel shell</td>
<td>196</td>
<td>7850</td>
<td>200</td>
<td>520</td>
</tr>
</tbody>
</table>

Table 2. Material properties for structural analysis

Fig. 2. The model of Cu wire wound coil
The magnetic problem involves the static magnetic field analysis in a space around the coil and in the reinforced turns of the coil. Electromagnetic fields are governed by the Maxwell’s equations [11] for vector magnetic potential:

\[ \nabla \times \{H\} = \{J_s\}, \quad (1) \]
\[ \nabla \cdot \{B\} = 0 \quad (2) \]

where \(\{H\}\) – is magnetic field intensity vector, \(\{B\}\) – is magnetic flux density vector, \(\{J_s\}\) – is applied source current density vector, while \(\nabla\) – is notation of the divergence operator of a vector.

Current density in a coil can be obtained from the equation:

\[ J = \frac{n \cdot I}{S} \quad (3) \]

where \(n\) – is a number of turns, \(I\) – is a total current, \(S\) – is a cross-sectional area of the coil.

The structural problem involves the mechanical analysis of the coil structural parts. The general deformations at the each point of finite elements are expressed as the sum of elastic and plastic deformations:

\[ d\{e\} = d\{e^e\} + d\{e^p\} \quad (4) \]

where \(\{e^e\}\) – is elastic deformation, \(\{e^p\}\) – is plastic deformation.

For 2-D model the plastic behavior of a material, characterized by no recoverable strain, begins when the stresses exceed the material’s yield point, i.e. correspond the von Mises yield criteria [11-12].

4. SIMULATION RESULTS

Using the ANSYS software the distribution of magnetic field intensity and magnetic field intensity, distribution of Lorenz force density and total deformations in the Cu wire wound coils was established (see Figures 3-4).

In the range of maximum allowable stresses the magnetic field flux density reaches the 40 T (see Figure 3). Maximum values of coil residual displacements reaches: axial displacements of Cu wire wound coil – 0.07 mm, radial displacements – 0.27 mm (see Figure 4). In this case radial magnetic forces are general destructive loads. Calculation results shows that total displacements of analysed Cu wire wound coil with interlayer reinforcement and steel shell are enough low and not exceed the material’s ductility, accordingly this coil rigidity is widely increased.

5. TEST RESULTS

According numerical simulation and construction optimisation results the coil
was manufactured and tested. For the training procedure, the impulse magnet was immersed in liquid nitrogen. The coil has generated 10 pulses about 40 T and remained stable (see Figure 5).


6. CONCLUSION

Numerical analysis of magnetic field distribution, magnetic forces distribution, deformations analysis of pulsed solenoids was done. Due to geometric symmetry of simulated object 3-D finite element modelling was simplified to 2-D numerical modelling and relatively good results are achieved. It was found that mechanical strength of winding materials is one of most limited factor to insure mechanical strength of pulsed solenoid. These findings indicate a successful design of pulsed magnet.

7. REFERENCES
