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An Analytical Technique to Elucidate Field Impurities From Manufacturing Uncertainties of a Double Pancake Type HTS Insert for High Field LTS/HTS NMRMagnets

Seung-yong Hahn, Min Cheol Ahn, Emanuel Saul Bobrov, Juan Bascuñán, and Yukikazu Iwasa

Abstract—This paper addresses adverse effects of dimensional uncertainties of an HTS insert assembled with double-pancake coils on spatial field homogeneity. Each DP coil was wound with Bi2223 tapes having dimensional tolerances larger than one order of magnitude of those accepted for LTS wires used in conventional NMR magnets. The paper presents: 1) dimensional variations measured in two LTS/HTS NMR magnets, 350 MHz (LH350) and 700 MHz (LH700), both built and operated at the Francis Bitter Magnet Laboratory; and 2) an analytical technique and its application to elucidate the field impurities measured with the two LTS/HTS magnets. Field impurities computed with the analytical model and those measured with the two LTS/HTS magnets agree quite well, demonstrating that this analytical technique is applicable to design a DP-assembled HTS insert with an improved field homogeneity for a high-field LTS/HTS NMR magnet.

Index Terms—Bi2223 tape, double-pancake coils, field homogeneity, HTS insert, LTS/HTS NMR magnet, manufacturing uncertainty, stochastic method.

I. INTRODUCTION

This paper addresses adverse effects of dimensional uncertainties of an HTS insert assembled with double-pancake coils on spatial field homogeneity. Each DP coil was wound with Bi2223 tapes having dimensional tolerances larger than one order of magnitude of those accepted for LTS wires used in conventional NMR magnets. The paper presents: 1) dimensional variations measured in two LTS/HTS NMR magnets, 350 MHz (LH350) and 700 MHz (LH700), both built and operated at the Francis Bitter Magnet Laboratory; and 2) an analytical technique and its application to elucidate the field impurities measured with the two LTS/HTS magnets. Field impurities computed with the analytical model and those measured with the two LTS/HTS magnets agree quite well, demonstrating that this analytical technique is applicable to design a DP-assembled HTS insert with an improved field homogeneity for a high-field LTS/HTS NMR magnet.

II. MANUFACTURING UNCERTAINTY OF H50 AND H100

A. Manufacturing Tolerance of HTS Tape and LTS Wire

Table I summarizes geometric parameters of two HTS tapes and one LTS wire used respectively for H50, H100, and L300. The “uncertainty” in this paper is defined as $U_x$ in (1) where $x$ is a dimensional variable and $\Delta x$ is its deviation.

$$U_x = \frac{\Delta x}{x} \times 100 \quad \text{[\%]}$$  \hspace{1cm} (1)

The manufacturing tolerances and uncertainties of HTS tapes are ~10 times larger than those of LTS wire. The large tolerances of HTS tapes lead to dimensional uncertainties in DP coils, which in turn lead to spatial field impurities of the HTS inserts in the two LTS/HTS NMR magnets.
TABLE II
DESIGNED AND MEASURED PARAMETERS OF H50 AND H100

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Designed</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP i.d., o.d. [mm]</td>
<td>78; 120.3</td>
<td>78; 126.5</td>
</tr>
<tr>
<td>DP height [mm]</td>
<td>6.38</td>
<td>8.33</td>
</tr>
<tr>
<td>Number of double pancake coils</td>
<td>50</td>
<td>48</td>
</tr>
<tr>
<td>Pancake-pancake gap [mm]</td>
<td>0.178</td>
<td>0.127</td>
</tr>
<tr>
<td>Overall coil length [mm]</td>
<td>327.6</td>
<td>405.6</td>
</tr>
<tr>
<td>Operating current [A]</td>
<td>49</td>
<td>116</td>
</tr>
<tr>
<td>Center field [T]</td>
<td>1.27</td>
<td>2.35</td>
</tr>
<tr>
<td><strong>Measured o.d.</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>average; SD [mm]</td>
<td>118.30</td>
<td>1.06</td>
</tr>
<tr>
<td>Max; min [mm]</td>
<td>119.63</td>
<td>126.61; 1.18</td>
</tr>
<tr>
<td>Uncertainty [%]</td>
<td>0.90</td>
<td>0.93</td>
</tr>
<tr>
<td><strong>Measured height</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>average; SD [mm]</td>
<td>6.65; 0.125</td>
<td>8.66; 0.122</td>
</tr>
<tr>
<td>Max; min [mm]</td>
<td>6.99; 6.43</td>
<td>8.83; 8.28</td>
</tr>
<tr>
<td>Uncertainty [%]</td>
<td>1.88</td>
<td>1.41</td>
</tr>
</tbody>
</table>

*Uncertainty is defined as a standard deviation divided by an average.

B. Dimensional Uncertainties of DP Coils in H50 and H100

After each DP coil in H50 and H100 was wound according to the dimensions designed in Table II, its o.d. and height were measured—i.d. of each DP coil is identical to the o.d. of a winding bobbin. The dimensional variations of all DP coils' i.d. and height in H50 and H100 are shown in Fig. 1; Dotted line with solid-square and solid line with solid-circle represent average normalized o.d. and height, respectively. Note that the y-axis in Fig. 1 is “average normalized,” i.e. a solid line in each Figs. 1(a) and 1(b) indicates an average o.d. or height of DP coils in H50 or H100. Table II includes calculated averages and standard deviations from the measured values of o.d. and height; o.d. and height of upper and lower pancake coils were measured individually and averaged to define those of a single DP coil, respectively. As seen in Fig. 1 and Table II, the uncertainty of DP height is generally larger than that of o.d. in both H50 and H100, which corresponds to the 10 times larger tolerance of the HTS tape width than that of the thickness in Table I. As will be seen in Section III, the uncertainty of DP height had more impact on spatial field impurity of H50 and H100 than that of o.d.

III. SENSITIVITY OF ZONAL FIELD GRADIENTS

A. Zonal Harmonics Calculation

Because of azimuthal symmetry of ideal DP coils, an axial field, $B_z$, along the magnet axis can be expressed by (2) where all tesseral harmonics disappear and only zonal harmonics remain [3]. In this paper, we deal with zonal field gradients up to the 4th order—$Z1, Z2, Z3,$ and $Z4$, which corresponds to $2A2, 3A3, 4A4,$ and $5A5$ in the (2), respectively [4].

$$B_z(z) = \sum_{n=0}^{\infty} (n+1)A_{n+1}z^n \quad (2)$$

B. Sensitivity Analysis

Sensitivity of the ith order zonal gradient, $S_{Zi}$, is defined as

$$S_{Zi} = \frac{\partial Z_i}{\partial x} \quad i = 1, 2, 3, 4 \quad (3)$$

where $Z_i$ is the ith order zonal gradient and $x$ is a target variable such as o.d. or height of a pancake coil.

A sensitivity analysis of field gradients up to the 4th order in H50 and H100 was performed under an operating condition of 350.2312 MHz in LH350 (42 MHz from H50) and 587.5801 MHz in LH700 (96 MHz from H100). Fig. 2 presents analysis results where x-axis indicates the order of stacked pancake coils in H50 or H100; In general, the sensitivity of height uncertainty is larger than that of o.d. Note that the uncertainties of ~20 pancake coils positioned near the insert axial center have dominant impact on field homogeneity; the uncertainty effect of the other DP coils on field homogeneity is negligible. From the maximum sensitivity of each gradient in Fig. 2 multiplied by the standard deviation of o.d. or height in Table II, potential zonal gradients from a single uncertainty of the largest sensitivity o.d. or height
TABLE III  
POTENTIAL ZONAL GRADIENTS FROM A SINGLE UNCERTAINTY OF THE LARGEST SENSITIVITY O.D. OR HEIGHT; MEASURED GRADIENTS INCLUDED

<table>
<thead>
<tr>
<th>Field gradients</th>
<th>H50</th>
<th>LH350</th>
<th>H100</th>
<th>LH700</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>o.d.</td>
<td>height</td>
<td>Measured*</td>
<td>o.d.</td>
</tr>
<tr>
<td>Z1 [Hz/cm²]</td>
<td>6763</td>
<td>12987</td>
<td>63922 (34)</td>
<td>15821</td>
</tr>
<tr>
<td>Z2 [Hz/cm²]</td>
<td>3078</td>
<td>4836</td>
<td>8810 (57)</td>
<td>6953</td>
</tr>
<tr>
<td>Z3 [Hz/cm²]</td>
<td>758</td>
<td>912</td>
<td>-7181 (62)</td>
<td>1657</td>
</tr>
<tr>
<td>Z4 [Hz/cm²]</td>
<td>251</td>
<td>275</td>
<td>-768 (84)</td>
<td>534</td>
</tr>
</tbody>
</table>

*The number in parenthesis presents a standard deviation of each gradient from statistical field mapping analysis [4].

IV. STOCHASTIC ESTIMATION OF SPATIAL FIELD HOMOGENEITY

A. Stochastic Approach to Estimate Spatial Field Impurity

The axial field of an HTS insert is a function of the o.d. and height of individual pancake coils as expressed in (4) where \(d_i\) and \(h_i\) are an o.d. and height of the \(i\)th pancake coil respectively and \(N_{PC}\) is a total number of pancake coils. In the proposed statistic analysis, \(d_i\) and \(h_i\) are ranged as seen in (5) where \(d_{avg}\) and \(h_{avg}\) are the designed o.d. and height, respectively, and \(\Delta d_{MAX}\) and \(\Delta h_{MAX}\) are their estimated maximum tolerance.

\[
B_i(d_i, h_i) \quad i = 1, \ldots, N_{PC} \\
\left| d_i - d_{avg} \right| \leq \Delta d_{MAX}, \quad \left| h_i - h_{avg} \right| \leq \Delta h_{MAX}
\]

Using a random number generator in a FORTRAN code, more than a million cases with all different \(d_i\) and \(h_i\) within the range of (5) are examined and an average and standard deviation of zonal gradients and a peak-to-peak field homogeneity within a target DSV (Diameter Spherical Volume) can be obtained.

B. Field Impurity Estimation of H50 and H100 Using the Proposed Stochastic Analysis

The proposed stochastic analysis was applied to H50 and H100. In the analysis, \(d_{avg}\) and \(h_{avg}\) were set to the measured averages in Table II where \(\Delta d_{MAX}\) and \(\Delta h_{MAX}\) to the maximum deviations of respective o.d. and height between the average and measured values shown in Fig. 1.

Table IV summarizes the results of the stochastic analysis applied to H50 and H100 under the operating condition of 350 MHz in LH350 (42 MHz from H50) and 587.5801 MHz in LH700 (96 MHz from H100). Note that the standard deviations of zonal gradients in Table IV are generally larger than averages, which reveals the significant impact of the geometric
Table IV

<table>
<thead>
<tr>
<th>Field gradients</th>
<th>LH350</th>
<th>LH700</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z1 [Hz/cm]</td>
<td>2649</td>
<td>5938</td>
</tr>
<tr>
<td>Z2 [Hz/cm]</td>
<td>9769</td>
<td>16095</td>
</tr>
<tr>
<td>Z3 [Hz/cm]</td>
<td>-261</td>
<td>-520</td>
</tr>
<tr>
<td>Z4 [Hz/cm]</td>
<td>-101</td>
<td>-98</td>
</tr>
<tr>
<td>3-cm DSV [ppm]</td>
<td>271</td>
<td>347</td>
</tr>
</tbody>
</table>

uncertainties of DP coils in the HTS inserts on the field gradients of the LTS/HTS NMR magnets.

Assuming that the zonal gradients and the overall 3-cm DSV homogeneities from the stochastic analysis follow a Gaussian distribution of an average and standard deviation in Table IV, we may mark, on a standard normal distribution in Fig. 3, the measured gradients in Table II and the overall 3-cm-DSV peak-to-peak homogeneities of 438 ppm in LH350 and 308 ppm in LH700 which were obtained from the measured zonal gradients without tesseral gradients contribution. Most of zonal gradients and 3-cm DSV homogeneities, except the Z1 and Z3 in H50, are located within the range of one standard deviation in Fig. 3. This implies that the proposed method with a designed parameter as an average and an estimated manufacturing uncertainty as a standard deviation may be used to statistically estimate a potential field impurity of a DP-assembled HTS insert even before it is constructed.

V. Conclusion

Effects of manufacturing uncertainties, chiefly of dimensional, on spatial field homogeneity in a double-pancake (DP) type HTS insert were investigated. According to the analyses in this paper, we may conclude that:

- Dimensional tolerances of Bi-2223 HTS tape, if much greater than those acceptable to LTS wires, lead to uncertainties in geometric parameters of DP coils. When such DP coils are assembled into an HTS insert for a high-field LTS/HTS NMR magnet, these tolerances become a source of “large” field impurities.
- Height uncertainties of DP coils have more adverse effects on zonal field gradients than those of o.d..
- According to a sensitivity analysis, these uncertainties are likely sources of the measured field impurities in H50 and H100, particularly of the unexpectedly large zonal gradients.
- These uncertainties in the pancake coils, about 20 of them, positioned near the centers of H50 and H100 have dominant impacts on field homogeneity; those in the rest have negligible effects.
- Spatial field impurity originating from manufacturing uncertainties of a DP-assembled HTS magnet can be estimated by the statistical analysis described in this paper.
- Validity of the stochastic method presented here was verified by good agreement between the field homogeneities estimated by this method and those measured in LH350 and LH700.
- The analytical technique described here can be used to design an improved field homogeneity DP-assembled HTS insert for a high-field LTS/HTS NMR magnet by focusing on not an ideally designed field homogeneity but a stochastically predicted one.

Acknowledgment

The authors thank the late Emanuel Saul Bobrov (1937–2008), our colleague and a long time member of the Magnet Technology Division, for his outstanding and distinguished contributions to many areas of magnet technology, including the subject matter of this paper.

References