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# A simulation study on the variation of virtual NMR signals by winding, bobbin, spacer error of HTS magnet

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**Abstract**

Recently, production technique and property of the High-Temperature Superconductor (HTS) tape have been improved. Thus, the study on applying an HTS magnet to the high magnetic field application is rapidly increased. A Nuclear Magnetic Resonance (NMR) spectrometer requires high magnitude and homogeneous of central magnetic field. However, the HTS magnet has fabrication errors because shape of HTS is tape and HTS magnet is manufactured by winding HTS tape to the bobbin. The fabrication errors are winding error, bobbin diameter error, spacer thickness error and so on. The winding error occurs when HTS tape is departed from the arranged position on the bobbin. The bobbin diameter and spacer thickness error occur since the diameter of bobbin and spacer are inaccurate. These errors lead magnitude and homogeneity of central magnetic field to be different from its ideal design. The purpose of this paper is to investigate the effect of winding error, bobbin diameter error and spacer thickness error on the central field and field homogeneity of HTS magnet using the virtual NMR signals in MATLAB simulation.

*Keywords*: NMR magnet, HTS magnet, Manufacturing error, Fabrication error , Winding error, Spacer thickness error, Bobbin diameter error

## 1. INTRODUCTION

Recently, production technique and property of the High Temperature Superconductor (HTS) tape have been improved. In particularly, critical current density of HTS tape according to magnetic field is greater than that of Low Temperature Superconductor (LTS) wire. Thus, the HTS magnet can generate the higher field than LTS magnet. In addition, magnitude of magnetic field of LTS magnet tends to be saturated. For these reasons, a research for obtaining the higher magnetic field using the HTS magnet is in progress to overcome the limitation of the maximum magnetic field of the LTS magnet. This research is currently conducted in Nuclear Magnetic Resonance (NMR) spectrometer because the magnitude of central magnetic field is significant factor in the NMR spectrometer [1, 2]. Moreover, homogeneity of magnetic field is important factor in NMR spectrometer. In other words, the larger magnitude of central magnetic field and the more homogenous of magnetic field, the better system it is. However, the homogeneity and magnitude of magnetic field are affected by fabrication errors in the HTS magnet [3, 4]. The reasons about occurrence of the fabrication errors are firstly the substitution to tape-shaped HTS from filament-shaped LTS and secondly manufacturing method of HTS magnet that the HTS tape is wound on the bobbin. Due to these reasons, unexpected fabrication errors may be occurred during manufacturing the HTS magnet. The fabrication errors are winding error, bobbin diameter error, spacer thickness error, wire-width error, wire-thickness error and so on. Some of fabrication errors are illustrated in Fig. 1. The wire-thickness and wire-width errors are caused not during manufacturing HTS magnet but producing the wire. Thus, these errors are uncontrollable during manufacturing the HTS magnet. Whereas, the winding, bobbin diameter and spacer thickness errors are caused during manufacturing the HTS magnet. Thus, these errors are controllable during manufacturing the HTS magnet. These errors would be unexpectedly occurred and affect the magnitude and homogeneity of central magnetic field. Consequently, the purpose of this paper is investigating the effect of winding error, bobbin diameter error and spacer thickness error on the magnitude and homogeneity of central magnetic field about the HTS magnet using virtual NMR signals in MATLAB simulation.

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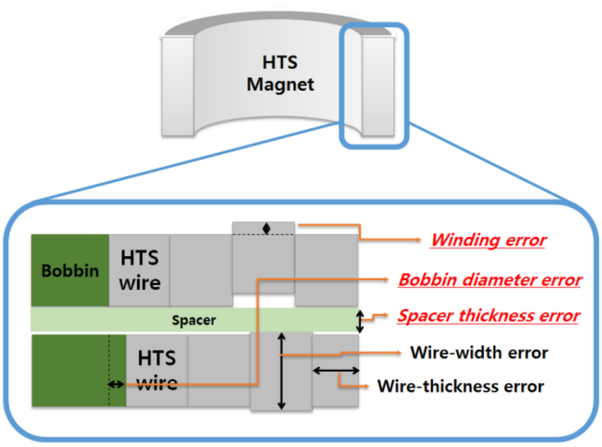



Fig. 1. Type of fabrication errors.

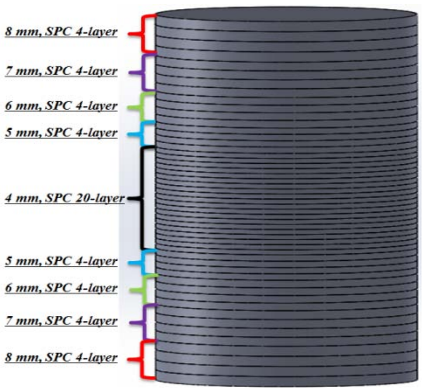



Fig. 2. Shape of virtual HTS magnet.

TABLE I
DESIGNED PARAMETER OF VIRTUAL HTS MAGNET.

| Parameter | Value |
|---|---|
| Central magnetic field | 11.4 T |
| Operating current | 240 A |
| Wire thickness | 0.14 mm |
| Turns per layer | 200 |
| Spacer thickness | 1 mm |
| Bobbin outer diameter | 35 mm |
| Bobbin inner diameter | 32 mm |

## 2. SIMULATION SET-UP

2.1. Specification of virtual HTS magnet

Recently, the SuNAM Co. manufactured multi-width no-insulation superconducting magnet using GdBCO HTS tape [5]. A specification and shape of virtual HTS magnet for using simulation are modeled with reference to this HTS magnet. The shape of the virtual HTS magnet is illustrated in Fig. 2 and virtual HTS magnet is constructed with 52 layer Single Pancake (SPC) using multi-width HTS tape. The SPC is stacked same order and number as shown in Fig. 2. Thus, the shape of virtual magnet is vertically symmetric with respect to the layer in order of 4 mm set of SPCs. The SPC is wound 200 turns HTS tape per layer. The inner diameter and outer diameter of magnet is respectively 32 mm, 35 mm, operating current is 240 A and central magnetic field is approximately 11.4 T about no-error model magnet. The other specifications are on Table I.

2.2. Specification of errors

Three types of error, winding, bobbin diameter and spacer thickness are illustrated in Fig. 3. Firstly, the winding error is caused because the HTS coil is manufactured by winding the HTS tape to bobbin. Shown in Fig. 3(a), the winding error represents the deviation of HTS tape from the reference line, ideally winding line. The direction of deviation is perpendicular to direction of winding and the deviation is occurred one direction. The winding error is set up by each turn of each SPC. Secondly, shown in Fig. 3(b), the bobbin diameter error is variation about the outer diameter of bobbin that is less or greater than 35 mm. This error affects the starting position of HTS tape. This error model is applied to all bobbin. Thirdly,

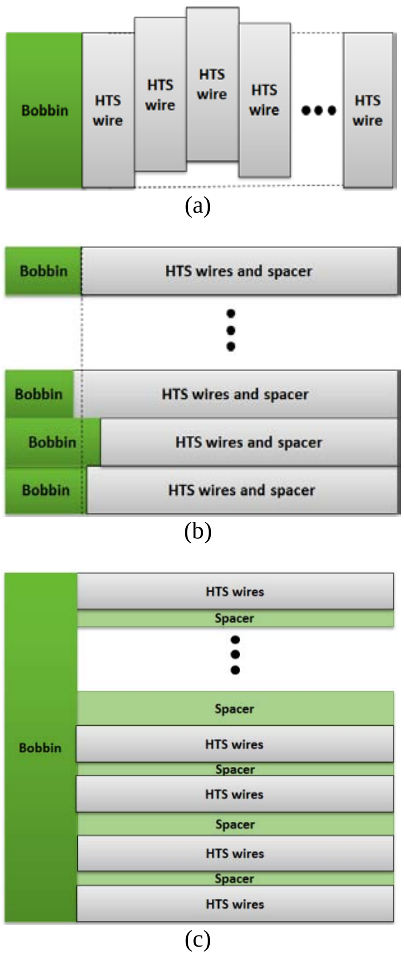


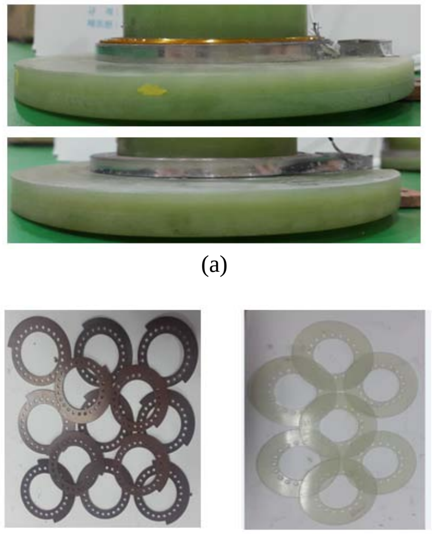

Fig. 3. Description of (a) winding error, (b) bobbin error and (c) spacer thickness error, and the dashed line is reference line of no-error model.

shown in Fig. 3(c), the spacer thickness error represents that the spacer thickness is less or greater than 1 mm. This error model is applied to the all 52 spacers. Fig. 4 shows a photograph of HTS coils, bobbins and spacers which are manufactured each with using 4.8 mm HTS tapes, 65 mm outer diameter and 1mm thickness. To set the magnitude of the variation error of samples were measured. The fabrication errors were set up by using a normal distribution. The fabrication errors were represented in a range of measured errors by adjusting the standard deviation of normal distribution. The measured fabrication error of samples and standard deviation of normal distribution are represented in Table II.

## 3. SEQUENCE AND DESCRIPTION OF SIMULATION

3.1. Modeling of virtual magnet

The purpose of this paper is to investigate the effect of the fabrication errors on magnitude and homogeneity of magnetic field of HTS magnet. A no-error magnet that does not have fabrication errors is firstly modeled in order to compare with other error models. Then, three types of virtual HTS magnets with error are modeled. Therefore, totally four virtual HTS magnets of no-error, winding,



(a)

(b)

Fig. 4. Photograph of (a) HTS coils and (b) Spacers.

TABLE II
DEVIATION OF MEASURED ERROR ABOUT SAMPLES
AND STANDARD DEVIATION OF NORMAL DISTRIBUTION.

| | Winding error | Spacer thickness error | Bobbin diameter error |
|---|---|---|---|
| Measured error (mm) | 0.12 | $\pm$0.05 | $\pm$0.05 |
| Standard deviation (mm) | 0.10/1.65 | 0.05/1.65 | 0.05/1.65 |

bobbin diameter and spacer thickness error were modeled.

3.2. Calculation and mapping of the magnetic field

In NMR spectrometer, magnitude and homogeneity of magnetic field is significant in the certain area that is Diameter of Spherical Volume (DSV). Shown in Fig. 5, the DSV is sphere with 30 mm-diameter in center of modeled virtual HTS magnet. Then, many points on the z-axis of DSV were selected and at that points, the magnitude of magnetic field were calculated. The magnetic field was calculated by MATLAB code using Biot-Savart law. The accuracy of calculation is 0.1 ppm. Then, equation of magnitude of magnetic field for z-axis was derived by (1).

$$B_Z(x,y,z) = A_{10} + 2A_{20}Z + 3A_{21}X + 3B_{21}Y + 3A_{30}\left(Z^2 - \frac{R^2}{2}\right) + 12A_{31}ZX + 12B_{31}ZY + 15A_{32}(X^2 - Y^2) + 15B_{32}2XY + 4A_{40}\left(Z^3 - \frac{3ZR^2}{2}\right) + 30A_{41}\left(Z^2X - \frac{XR^2}{4}\right) + 30B_{41}\left(Z^2Y - \frac{YR^2}{4}\right) + 90A_{42}Z(X^2 - Y^2) + 90B_{42}2XYZ + 105A_{43}(X^3 - 3XY^2) + 105B_{43}(3X^2Y - Y^3) \quad (1)$$

The X, Y and Z are point of rectangular coordinate in DSV, A and B are spherical harmonic coefficients and $R = X^2 + Y^2$ is distance between the point with origin. Using this equation, it is possible to obtain magnetic field at any point in DSV.

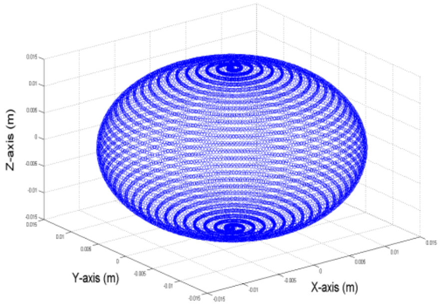



Fig. 5. Mapping points on the surface of DSV.

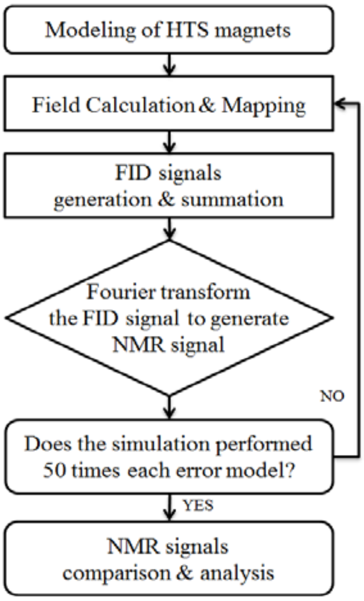



Fig. 6. Flow chart of simulation.

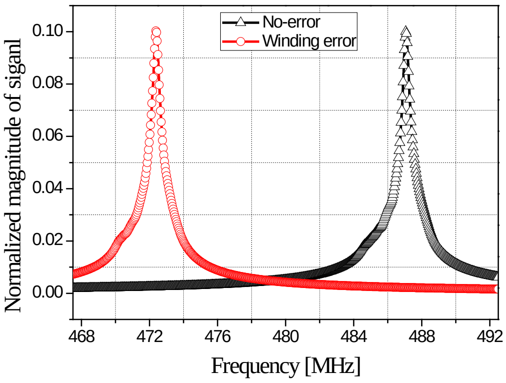
3.3. Generation of FID signal and NMR signal

Shown in Fig. 5, many points were selected to genertate the Free Induction Decay(FID) signal. The FID signal is sinusoidal, exponential and time domain primitive function of NMR signal. Then, the FID signal is converted to the NMR signal using Fourier transform. Finally, the NMR signal is obtained. This simulation is conducted 50 times for each error model and 1 time for no-error model for comparison. The detailed flow chart of simulation is represented in Fig. 6.

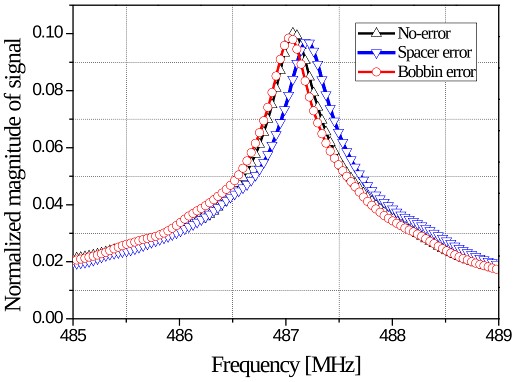
## 4. RESULT AND DISCUSSION

4.1. The magnitude of magnetic field

The results on the Table III represent average of magnitude of magnetic field about 50 samples of each error model. Fig. 7 (a) shows virtual NMR signals about the winding error and no-error model in the frequency range of 25 MHz. Center axis of NMR signal about winding error model is shifted left by 15.188 MHz comparing with that of no- error model. This result shows that the magnitude of magnetic field in DSV of winding error model is decreased about 0.3568 T. Whereas, differences of center axis of NMR and magnitude of




(a)




(b)

Fig. 7. Normalized signal strength of NMR according to the frequency.

TABLE III
MAGNETIC FIELD STRENGTH RESULTS OF SIMULATION

| | No-error | Winding error | Bobbin error | Spacer error |
|---|---|---|---|---|
| Center axis (MHz) | 486.859 | 471.671 | 486.855 | 486.948 |
| Difference (MHz) | - | 15.188 | 0.004 | 0.089 |
| Magnetic field (T) | 11.4367 | 11.0799 | 11.4366 | 11.4388 |
| Difference (T) | - | 0.3568 | 0.0001 | 0.0021 |

TABLE IV
HOMOGENEITY RESULTS OF SIMULATION

| | No-error | Winding error | Bobbin error | Spacer error |
|---|---|---|---|---|
| Homogeneity of samples | 0.0080 | 0.0063 to 0.0091 | 0.0074 to 0.0085 | 0.0074 to 0.0102 |
| Average of samples | 0.0080 | 0.0075 | 0.0081 | 0.0084 |

magnetic field in DSV in case of bobbin diameter error and spacer thickness error model are smaller compared with the winding error model. In Fig. 6(b) and Table III, the differences of center axis of NMR and magnitude of magnetic field between bobbin diameter error model and no-error model are respectively 0.004 MHz, 0.0001 T and spacer thickness error model and no-error model are respectively 0.089 MHz, 0.0021 T.

4.2. Result of magnetic field homogeneity

The homogeneity of magnetic field is described by differences between the maximum and minimum magnetic field in DSV. Results of homogeneity of magnetic field accordance with each error model are represented in Table IV. The results are normalized by average magnetic field in DSV. Compared with the no-error model, the homogeneity of magnetic field is varied by fabrication error. The results of each error model have both worse and better case. The average variation of the magnetic field homogeneity of bobbin diameter error and spacer thicknesse error model is increased and that of winding error is decreased compared with no-error model.

## 5. CONCLUSION

The results of simulation show that the fabrication errors, winding, spacer thickness error, bobbin diameter error affect to the magnitude and homogeneity of magnetic field of HTS magnet.

The conclusions are summarized as follow:

1) Magnitude of magnetic field is significantly decreased in simulation of winding error model compared with other error models and no-error model.
2) Homogeneity of magnetic field is the more homogeneous in simulation of winding error model and worse other error models compared with no-error model.

Furthermore, further study is needed. Firstly, the replacement of the virtual HTS magnet is needed because it is not manufactured for the NMR spectrometer. Secondly, the consideration about variation of HTS magnet height according to magnitude of error is needed. Thirdly, other additional methods for analysis of the magnetic field are needed.

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