DESIGN OF MAGNET CONSOLE FOR NMR RIPENESS SENSOR USING ANSYS

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ABSTRACTS

A magnet console is critical element since its homogeneity is essential to the performance of a nuclear magnetic resonance(NMR) based sensor. Geometry and properties of magnet materials determine the magnetic flux density and homogeneity of the console.

This study is carried out to develop a design scheme of the magnet console using ANSYS to reduce the design error of the magnet console compared. To enhance the performance of the magnet console, corner steel was proposed and validated by simulation and manufactured one. The corner steel increased the magnetic flux density (B) by about 1 %, and enhanced homogeneity by approximately 3 times. There was about 3% difference between simulated and measured B values.

Keywords: NMR, Magnet Console, Finite Element Analysis, Moisture, Sensor

INTRODUCTION

Non-destructive quality measurement of agricultural products is a crucial research area in today's agriculture. Optics, NIR spectroscopy, Untrasonic Testing and Imaging, and NMR spectroscopy have been state-of-art technologies to be utilized for development of non-destructive quality sensors (Battocletti, 1985; Brusewitz, 1987; Cho, 1988; Bray, 1992). Specially, proton (^1H) NMR is most powerful technique for chemical analysis. Qualitative and quantitative analyses are possible non-destructively based on the resonant absorption and emission of magnetic energy of proton when subjected to a magnetic field (Martin, 1980).

The NMR-based sensor consists of a magnet console, probe and electronic circuits. Among the components of NMR sensor, magnet console is a basic element which produces a magnetic field. Usually, super-conducting magnet is used in medical instruments or chemical analyzer. Permanent magnet can be used for NMR-based agricultural sensors having about 1,000~2,000 gauss magnetic fields.

Proper design of the magnetic console using the permanent magnets is important to get desired magnetic flux density (B) and its homogeneity. Cho et al. (1990) developed a program to design magnet console of about 1,000 gauss using finite element method. They proposed a design using pole faces and shimming frames to enhance the homogeneity.

The goal of this study is 1) to improve the performance of the magnet console by conducting a simulation using ANSYS finite element analysis program, 2) find a new design factor, and 3) to reduce the measurement error.

MATERIAL AND METHODS

GEOMETRY OF MAGNET CONSOLE

There are two kinds of the magnet console configuration: box and cylinder types according to the shape of magnet. The box type was designed by Cho et al. (1990), as shown in Fig. 1. 12 design variables were used to specify the geometry of the magnet console. Descriptions of each parameter are listed in Table 1.

It was studied how magnetic flux density and homogeneity were influenced by each parameters. The Magnet console was designed by selection of an optimized assembly of these parameters. The air gap where agricultural products would be located was constraint in designing a magnet console. The shimming frames (d, k) and corner steels (l) were proposed to enhance magnetic flux density and homogeneity of the magnet console.

Furthermore, a magnet console with concave pole faces was designed and compared with the one having shimming frames and corner steels. Three kinds of magnet console were analyzed and are shown in Figure 2.

The performance of magnet console for the NMR-based sensor is evaluated by its magnetic flux density and homogeneity. Permanent magnet and geometry of the magnet console influence the magnetic flux density and the homogeneity.

MG-40 Gaussmeter (Walkers scientific, Inc.; ±0.05% error) was used to measure the magnetic flux density. The homogeneity of magnetic field was calculated using equation (1).

$$\text{Homogeneity} = \frac{\text{Maximum deviation of magnetic fields}}{\text{Average magnetic field}} \times 10^6 \; [ppm] = \frac{\left|\Phi_i - \Phi_{avg}\right|_{max}}{\Phi_{avg}} \times 10^6 \; [ppm] \qquad \ldots\ldots\ (1)$$

DESIGN OF MAGNET CONSOLE USING FINITE ELEMENT ANALYSIS

A finite element method has been powerful tool in problem solving in statics, dynamics, thermodynamics, fluid dynamics, and many other researches. Electromagnetics is also included in the subject of finite element methods. Many commercial packages such as ABAQUS, NASTRAN, FLUENT, and ANSYS have been used in many researches. ANSYS(SASI-Swanson Analysis System, Inc.) 5.0 on SunSparc Workstation was used to design the magnet consoles

Finite Element Model for Permanent Magnet

Governing equations for the finite element model were Maxwell's equations on electromagnetic field analysis.

$$\nabla \times \vec{H} = \vec{J}$$

$$\vec{B} = \nabla \times \vec{\Phi} = \mu \cdot \vec{H} \qquad \ldots\ldots (2)$$

$$\nabla \cdot \vec{\Phi} = 0 \qquad where, \nabla = \vec{i}\frac{\partial}{\partial x} + \vec{j}\frac{\partial}{\partial y} + \vec{k}\frac{\partial}{\partial z}$$

Permanent Magnet Materials

It is important to choose an appropriate permanent magnet material for a low cost magnet console having the proper performance for the NMR sensor. Nd-Fe-B, Rare earth, and Ceramic magnets could be used. Ferrite (or ceramic 8) permanent magnet was chosen since it is relatively light and inexpensive. Property of a permanent magnet is described by μ (magnetic permeability) and demagnetization curve (B-H curve), which shows non-linear relation between magnetic flux density (B) and field intensity (H). Figure 3 shows the demagnetization curves of the ferrite permanent magnet and a low carbon steel under ambient temperature of 20°C.

RESULTS AND DISCUSSIONS

DESIGN PROGRAM FOR FINITE ELEMENT ANALYSIS

ANSYS includes APDL (ANSYS Parametric Design Language) which makes it easy to modularize, therefore, modify and update the analysis procedures. Pre-processing (modeling and mesh generation), solver, and post-processing modules were developed. 2D models for both X-Z plane and Y-Z plane were used for the analysis. Figure 4 shows the post-processing results of magnetic flux density in scalar quantities.

VALIDATION OF FINITE ELEMENT ANALYSIS FOR MAGNET CONSOLE

Results of finite element analysis should be validated with the measurement of manufactured prototype. Several prototype magnet consoles were manufactured and compared with the results of the finite element analysis. Ceramic 8 permanent magnet at the ambient temperature (20 °C) was used for the simulation. Magnetic flux density was measured at 21.5 °C. The magnetic flux density is dependent upon its temperature. The variance with temperature of ceramic 8 magnet is 0.19% loss/°C (Tebble, 1969).

Table 2 shows the specifications of the prototype magnet console which was used to validate the simulation results. Comparison of measured values with predicted values are shown in Table 3. Homogeneity was calculated within 25mm from the center of the air gap.

The difference between measured and predicted values was 26 gauss. The error was about 3%, considering the 1.5 °C temperature difference.

The optimum values of each part was searched to enhance the homogeneity of the magnet console. Finally, d = 20.0 mm, k = 17.8 mm were chosen, while other values did not change. The homogeneities were enhanced from 1196 ppm to 345 ppm (X-Z) and from 397 ppm to 116 ppm (Y-Z), but the magnetic flux density was reduced from 959 gauss to 956 gauss.

EFFECTS OF SHIMMING FRAME AND CORNER STEEL

The shimming frames and corner steels were added to enhance the homogeneity of magnet console.

Shimming Frame and Corner Steel

The shimming frame was expected to push the magnetic flux inward, therefore, to reduce the loss of magnetic flux at the outer part of air gap as shown in Figure 5.

To verify the effect of shimming frame, the magnet console without the shimming frame was analyzed. Results were compared with those of the magnet console with the shimming frame as shown in Table 4.

The shimming frame reduced the average magnetic flux density by 8.3% and improved the homogeneity by 75.2% (X-Z) and 97.6% (Y-Z). Therefore, to recover the reduced magnetic flux density, thickness (e), length (i), or width (a) of the permanent magnet should be adjusted. To minimize the effect on the homogeneity, thickness of the magnet was changed to increase the magnet flux density. The results are shown in Table 5. Addition of 10% (7.6 mm) of thickness of the permanent magnet restored the magnetic flux density approximately up to that of the magnet console without the shimming frame.

Corner Steel

Outer steel cover of which shape is rectangular makes a circuit for magnet field. Because of rectangular shape, at each corner, magnet field is concentrated and magnetic flux density peaks, thus the homogeneity at the center of air gap was degraded. Corner steel was expected to reduce the concentration of magnet field at each corner with no effects on the magnitude of magnetic flux density at the center of air gap. Installation of corner steel at 4 corners (X-Z plane) reduced the peak of magnetic flux density at each corner, but increased magnetic flux density at the center of air gap from 956 to 962, and enhances homogeneity up to 103 ppm (X-Z plane). Comparison results are shown in Table 6.

CONCLUSIONS

Magnet console is critical element for NMR based sensor since its homogeneity is essential to the performance of the sensor. The magnetic flux density and homogeneity of the console is dependent upon geometry and properties of materials. Therefore, a design scheme for the optimum design of the magnet console which is based on computer simulations is necessary.

This study was conducted to develop a design scheme of magnet console using ANSYS to reduce the design error compared with manufactured one. Shimming frame and corner steel were proposed to enhance the magnetic flux density and homogeneity of magnet console. As compared with previous study, design error was reduced from 4.7% to 2.64%.

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Table 1 Design parameters of the magnet console

Variable	Descriptions
a	Total width of magnet
b	Horizontal space gap (X-Z)
c	Thickness of steel cover
d	Width of shimming frame (X-Z)
e	Thickness of magnet
f	Thickness of pole face
g	Thickness of shimming frame
h	Air gap
I	Total length of magnet
j	Horizontal space gap (Y-Z)
k	Width of shimming frame (Y-Z)
l	Thickness of corner steel (X-Z)

Table 2 Specifications of a prototype magnet console

a	b	c	d	e	f	g	h	I	j	k
304.8	38.1	25.4	12.7	76.2	12.7	12.7	152.4	304.8	38.1	19.1

Table 3 Result of comparison of measured with predicted values

	Magnetic flux density (gauss)	Homogeneity (ppm)	
Measured	988 (1.5 °C temperature compensation)	1015 (X-Z)	1015 (Y-Z)
Predicted	959	1196 (X-Z)	397 (Y-Z)

Table 4. Comparison between the magnet consoles "with" and "without" the shimming frame

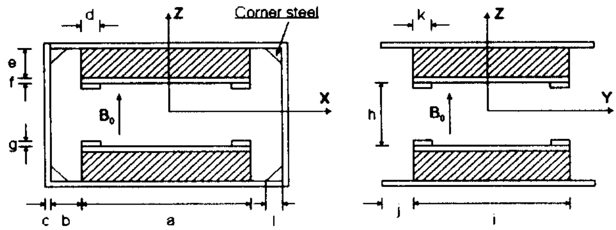
Shimming frame	Magnetic flux density (gauss)			Homogeneity (ppm)	
Installed	1242(X-Z)	669(Y-Z)	956 (average)	345(X-Z)	116(Y-Z)
Not installed	1363(X-Z)	723(Y-Z)	1043 (average)	1392(X-Z)	4776(Y-Z)

Table 5. Changes of magnetic flux density and homogeneity upon change of thickness of magnet (d = 20.3 mm, k = 17.8 mm)

Thickness (mm)	Magnetic flux density (gauss)			Homogeneity (ppm)	
76.2(Original)	1241(X-Z)	671(Y-Z)	956	345(X-Z)	116(Y-Z)
83.8(+10%)	1354(X-Z)	712(Y-Z)	1033	324(X-Z)	338(Y-Z)
91.4(+20%)	1386(X-Z)	751(Y-Z)	1069	339(X-Z)	355(Y-Z)

Table 6. Comparison results between magnet console "with" and "without" corner steel

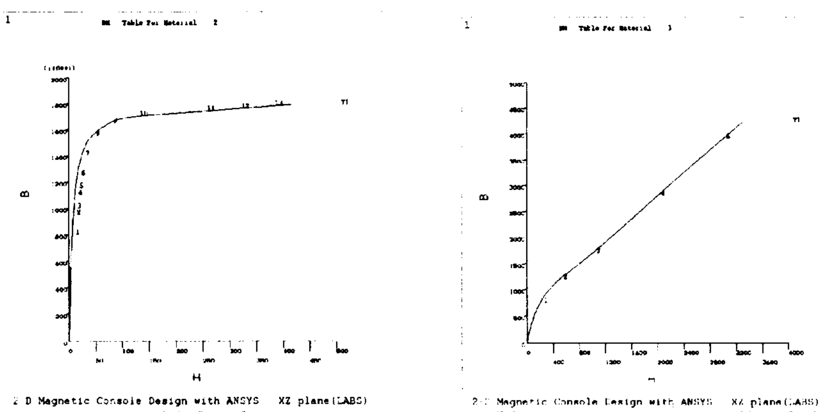
Corner steel	Magnetic flux density (gauss)	Homogeneity (ppm)
Installed	962 / 1255 (X-Z)	103 (X-Z)
Not installed	956 / 1242 (X-Z)	345 (X-Z)



(a) X-Z plane (b) Y-Z plane

Fig. 1 Magnet console configuration (box type)

Fig. 2 Three kinds of magnet console (a) with shimming frame and corner steel (b) without shimming frames nor corner steels



(a) Steel (b) Permanent Magnet (Ferrite)

Fig. 3 Demagnetization curves

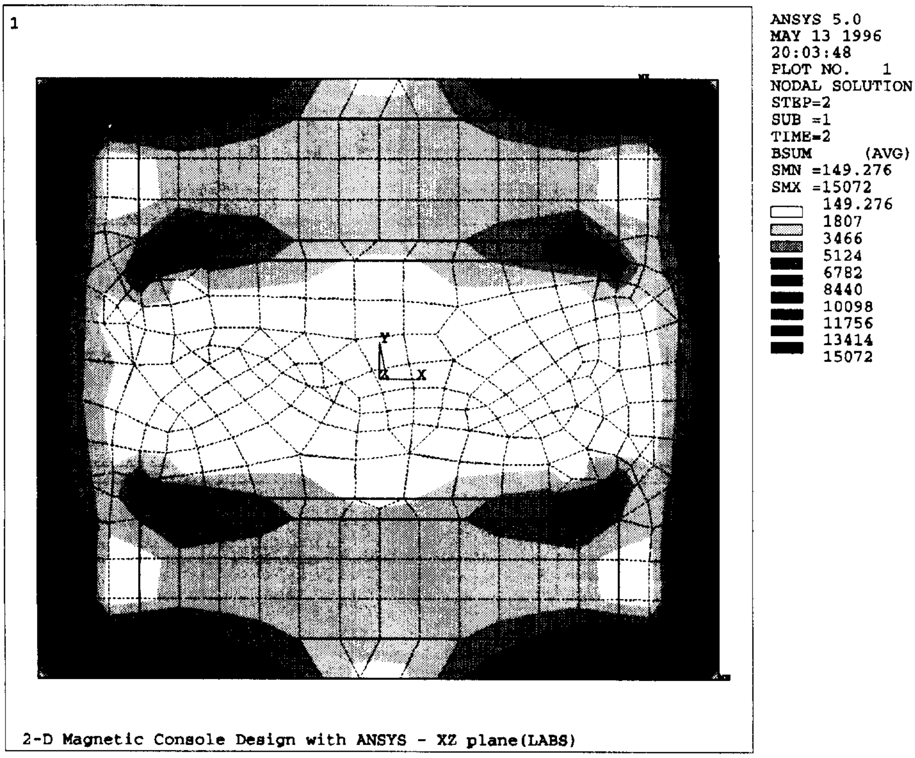
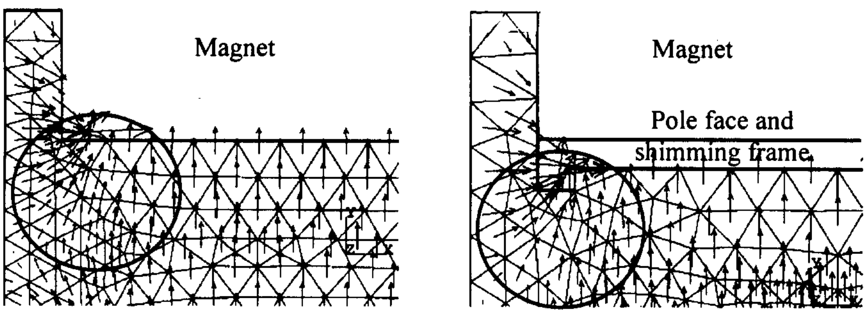


Fig. 4 Post-processing results of magnetic flux density in scalar quantity



(a) without the shimming frame

(b) with the shimming frame

Fig. 5 Vector plot of Magnet flux