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마그네토스트릭션 센서 성능 향상을 위한 바이어스 자기장의 위상 최적설계

Topology Optimization of a Bias Magnetic Field for the Performance Improvement of a Magnetostrictive Sensor

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ABSTRACT

A magnetostrictive sensor is used to measure stress waves propagating in a ferromagnetic cylinder without physical contact. The performance of a magnetostrictive sensor is affected most significantly by the bias magnetic field applied around the measurement location. The goal of this paper is to carry out the topology optimization of the bias magnet and yoke assembly to maximize the sensor output for traveling bending waves. We will use the multi-resolution topology optimization strategy to find the assembly of the bias magnet and the yoke that is easy to realize. The effectiveness of the present design is confirmed by an actual measurement of the sensor signal with the proposed bias magnet and yoke configuration.

1. Introduction

When a ferromagnetic material is subjected to time-varying mechanical stress or strain, the magnetic field changes. This phenomenon is known as the inverse magnetostriction effect or the Villari effect. Using this effect, a magnetostrictive sensor (MsS) can measure the mechanical properties in ferromagnetic materials. Since MsS does not need contact with the object, it can be applied for the on-line monitoring of rotating shafts. In addition, MsS can be used for the health monitoring of large-scale structures such as bridges and power plants, since MsS can produce elastic waves with high power.

MsS is simply composed of a coil part and a bias magnet part. The coil part is used to measure the change of the magnetic flux inside a ferromagnetic cylindrical test specimen such as a rod. Depending on the bias magnetic field configurations, longitudinal, torsional, or bending waves can be detected.

In this paper, we wish to find the optimal shape of the bias magnet of MsS that can produces the largest sensor output for traveling bending waves in a cylindrical steel beam. Kwun et. al. [1] and Cho et. al. [2] reported a simple bias magnet configuration for bending wave measurement. However, the bias magnetic field can be optimized to maximize the sensor performance.

In this paper, we carry out the topology optimization to find an optimal permanent magnet configuration. We use the density method and employ the optimality criterion (OC) method. However, we propose to use a multi-resolution strategy rather than the standard single-resolution strategy to obtain a better design. The numerical analysis of the magnetic field is based on the two-dimensional finite element model. To verify the usefulness of the present bias magnetic configuration, we present experimental results from the sensor with the

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present bias magnetic field.

2. Magnetostriction Effect

When a ferromagnetic material (such as Fe, Ni, Co and so on) is placed in a time-varying magnetic field, its physical dimension varies. This effect is known as the magnetostriction effect or Joule effect [3]. On the other hand, when a ferromagnetic material under a magnetic field is subjected to a change of a stress field, it exhibits the change in the amount of the magnetization. This reverse phenomenon is usually referred to as the inverse magnetostriction effect or the magnetomechanical effect [4].

At the crystalline level, ferromagnetic materials contain many magnetic domains. Within each domain, the atomic directions of the magnetic moment are identical. Since the magnetic domains are arranged at random in the absence of a bias magnetic field, there is no magnetic induction nearby. If the bias magnetic field is applied to the material, the domains are so arranged as to yield magnetic induction. With the presence of the bias field, the applied stress re-arranges the domains and produces the change of the magnetic induction.

If an applied stress is small and the applied bias magnetic strength is also small in a ferromagnetic waveguide, one may use the following linearized model to describe the magnetostriction effect [5,6]:

$$B = q\sigma + \mu^r H \qquad (1)$$

In equation (1), μ^r is the permeability under a constant stress state and q is the magnetoelastic coupling coefficient. The symbol B denotes the magnetic flux density induced by the magnetostriction effect and H, the magnetic field strength by the bias magnet.

To measure the change of the magnetic flux density inside the waveguide, it is encircled by the sensor coil. The change of the magnetic flux density is then converted to an electric signal on the ground of Faraday's law. Since the coil measures the time derivative of the magnetic flux, the last term of equation (1) can be ignored in evaluating the voltage output in the sensor coil. Therefore, the output voltage v of the coil can be written as

$$v = -N\int \frac{dB}{dt}\, dA = CN\int H\frac{d\sigma}{dt}\, dA \qquad (2)$$

where C denotes some constant and N, the number of turns of the sensing coil, A, the area of the coil cross section. It is clear from equation (2) that depending on stress waves to be measured, different distribution of the bias magnetic field must be provided.

For instance, the field distribution must be uniform throughout the cross section of the waveguide if uniform stress waves (i.e., longitudinal waves) are to be measured. In the case of bending wave propagation, the stress distribution across the cross section is linear [7] if we consider only the first branch of bending waves [8]. Therefore, the magnetic induction inside the waveguide must be linear.

Since the objective of this work is to maximize the sensor voltage output for bending waves, our design goal is equivalent to finding the configuration of the bias magnet and the yoke that produces a linear magnetic flux density component along the waveguide direction.

3. Optimization Problem

The waveguide in consideration is a solid circular cylinder, but a two-dimensional plane model may be used as a good approximation. This will simplify the subsequent numerical analysis. The objective of the present problem is to maximize the output voltage v at the sensor location.

The objective can be written as,

$$\textit{Maximize}: \quad v = \sum_i B_{xi}\sigma_{xi} \quad \textit{at measuring point} \qquad (3)$$

where i denotes the position along the cross section of the sensor (i.e. along the vertical direction) as shown in Figure 1. The symbol B_x denotes the component of the magnetic flux density vector in the x axis. This maximization problem is subjected to a volume constraint such as

$$\textit{Subjected to}: \sum v_e - V \le 0 \qquad (4)$$

where v_e is an element volume of a finite model and V

is the prescribed volume.

We wish to solve this problem as a topology optimization problem in a design domain marked in Figure 1. Since the sensor encircles the cylinder (here, modeled as a solid beam) and the bias magnets should be located at both sides of the cylinder. Therefore, the design domain is divided into two parts.

The two-dimensional finite element formulation of the analysis of the magnetostatic field is given by [9]

$$\boldsymbol{KA}=\boldsymbol{F}$$

where

$$\boldsymbol{K}=\frac{1}{\mu}\int\int\left(\frac{\partial \boldsymbol{N}^T}{\partial x}\frac{\partial \boldsymbol{N}}{\partial x}+\frac{\partial \boldsymbol{N}^T}{\partial y}\frac{\partial \boldsymbol{N}}{\partial y}\right)dxdy$$
$$\boldsymbol{F}=\int\int\left(H_{cx}\frac{\partial \boldsymbol{N}^T}{\partial y}-H_{cy}\frac{\partial \boldsymbol{N}^T}{\partial x}\right)dxdy \tag{5}$$

$$B_x=\frac{\partial \boldsymbol{N}^T}{\partial y}\boldsymbol{A} \tag{6}$$

where $\boldsymbol{A}$ denotes the magnetic vector potential, H_c, the coercive force, and $\boldsymbol{N}$, the shape function that the finite element employed.

Yoo [10] was the first who solved topology optimization in magnetic problems using the homogenization method. In this paper, the density method is employed instead of the homogenization method.

In the density method, the material properties μ and H_c of the design domain are modeled as functions of the design variables ρ's that are the densities of finite elements. The design variables ρ can vary from 0 to 1. If ρ is 0 (actually very close to 0), then the element is interpreted as an air element. On the contrary, if ρ becomes 1, it represents the permanent magnet. In this problem, therefore, we can penalize the material properties μ and H_c as

$$\mu=\mu(\rho)=\mu_0\{1+(\mu_m-1)\rho^n\} \tag{7}$$

$$H_c=H_c(\rho)=H_{cm}\rho^n \tag{8}$$

In the above equations, μ_0 and μ_m denote the permeability of the free space and the relative permeability of the permanent magnet respectively. H_{cm} denotes the coercive magnetic force of the permanent magnet and n denotes the penalty exponent.

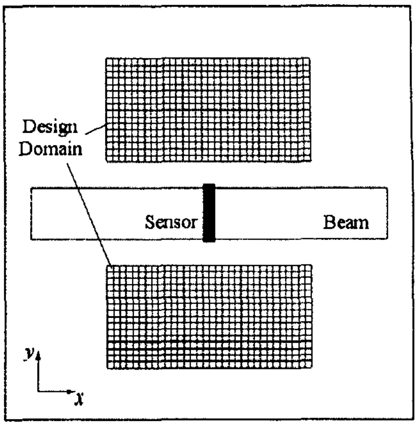

Figure 1 Schematic diagram of the analysis model for the optimal design of the bias magnet part of the magnetostrictive sensor.

The sensitivity of the objective function of equation (3) can be derived as

$$\begin{aligned}\frac{\partial v}{\partial \rho}&=\sum_i\frac{\partial B_{xi}}{\partial \rho}\sigma_{xi}\\&=\sum_i\frac{\partial \boldsymbol{N}^T}{\partial y}\left[\boldsymbol{K}^{-1}\left(\frac{\partial \boldsymbol{F}}{\partial \rho}-\boldsymbol{A}\frac{\partial \boldsymbol{K}}{\partial \rho}\right)\right]_i\sigma_{xi}\end{aligned} \tag{9}$$

4. Optimal Configuration and Verification

The analysis model for optimization is shown in Figure 1. The design domain is divided into the upper and lower parts as in Figure 1. Each element of the design domains represents a permanent magnet cell where all of the cells are arranged with their magnetic poles facing to the positive y direction.

As an optimizer, we employ the optimality criterion method [11] and use also the adjoint variable method [12] to facilitate the sensitivity analysis. In the optimization problem considered here, we use the volume constraint ratio of 15% and the penalty exponent of $n=3$. We do not use any filtering method.

First, we used the traditional single-resolution topology optimization method with 1024 design variables. The optimized result is shown in Figure 2. Note that there are gray regions, whose design variables take values between 0.3 and 0.7. Gray regions are usually

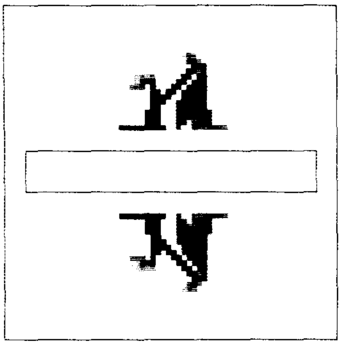

Figure 2 The optimal design by the standard single-resolution topology optimization technique. Its value of objective function is 24899. (Gray areas are interpreted as yokes.)

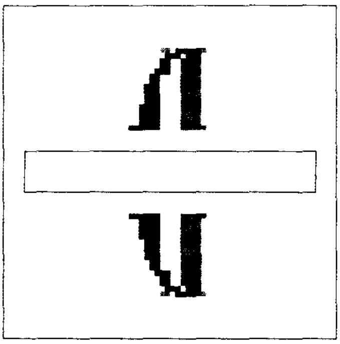

Figure 3. The optimized result by the multi-resolution strategy obtained in three resolution steps. Its value of objective function is 29362. Gray areas are interpreted as yokes.

regarded undesirable in general topology optimization problems because their interpretations are difficult. However, we claim that the gray regions can be interpreted as yokes: gray areas are needed to from a magnetic circuit better. The shape shown in Figure 2 produces some branches that do not contribute to sensor performance increase. Furthermore the system of the magnet and the yoke appears somewhat complex to produce.

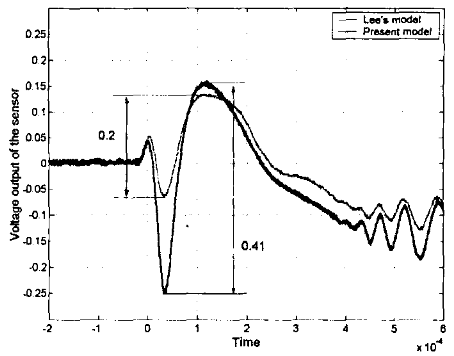

Figure 4 The measured bending wave signal by means of the present bias magnet field

This time, we make use of the multi-resolution topology optimization technique [13]. In the multi-resolution strategy, the design is carried out progressively with the dyadic increase in the design region division. The design at the previous resolution level is used as the initial guess at the next higher resolution level.

In this problem, the design was completed in three resolution steps. At the first step, only 64 design variables were used to discretize the design domain. At the second and third step, 256 and 1024 design variables were used, respectively. However, the analysis resolution for all design steps was based on the 1024 element division. The final result at the highest design resolution is shown in Figure 3. (For the detailed procedure, see [14])

We first remark that the objective value by the multi-resolution strategy has improved by 18% in comparison with that by the single-resolution strategy. Furthermore, the configuration of the magnet and the yoke by the multi-resolution strategy is simpler, which improves the manufacturability of the bias system.

To check the performance of the optimized design obtained by the topology optimization, the configuration shown in Figure 3 by the multi-resolution strategy was assembled. Using the sensor with the proposed system of the bias magnet and the yoke, an experiment was conducted. (See [15] for the experimental procedure and setup)

Figure 4 shows the bending wave signal measured by the present sensor and the one by the existing sensor configuration [6,16]. As clearly shown in Figure 4, the value of the first arriving peak that is measured by the present sensor has increased by as much as 210% in comparison with the existing sensor output.

5. Conclusions

We applied the topology optimization method to improve the performance of a magnetostrictive sensor to measure bending waves. The actual experiment confirmed that the optimized bias assembly of the magnet and the yoke, designed by the multi-resolution strategy, indeed yielded a greatly improved output.

Acknowledgement

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