Research on Air Gap Disturbance Compensation for Magnetoelastic Torque Sensors

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Abstract: Most of magnetoelastic torque sensors are very sensitive to air gap disturbances. To address this issue, this paper proposes two models to characterize the impact of air gaps on measurement. The magnetic circuit equation describes the impact of magnetic resistance changes caused by air gap disturbances on measurement, while the leakage flux equation describes the effective magnetic flux entering the magnetic circuit under different air gaps. Both models were subjected to finite element simulation and experimental verification, and the results obtained were very consistent with the model description, which can effectively improve the measurement accuracy, repeatability, and response frequency of the sensor.

Keywords: magnetostriction; magnetic circuit; air gap disturbance; leakage compensation

1 Research Background

The demand for high-performance torque sensors is increasing with the development of modern industry. The applications of traditional sensors are limited, because they require some changes to the measured system. Magnetoelastic sensors measure the torque by the change in magnetic permeability caused by stress, which can achieve non-contact dynamic measurement. However, most magnetoelastic torque sensors are very sensitive to changes in the air gap between the magnetic pole and the shaft to be measured. This paper conducts an in-depth study on this issue and explores the impact of air gap and the leakage magnetic flux caused by it on measurement.

2 Research Content

According to the inverse magnetostriction theory, The magnetic permeability of a ferromagnetic material will change when stress is applied, as shown in expression (1)[1]:

$\Delta\mu\mu = -2\lambda m B m 2\mu\sigma$ (1)

The probe forms a magnetic circuit with the shaft in experiment. The magnetic core, air gap and shaft serve as the magnetic medium and the excitation coil provides the magnetomotive force in this magnetic circuit. When stress is applied, the magnetic resistance of the magnetic medium changes, thus causes a change in the magnetic flux. The excitation coil applies a sinusoidal signal, causing alternating magnetic flux. The changing magnetic flux will generate electromotive force. Therefore, the change in the material's magnetic permeability can be known by measuring the signal in the induction coil, and then the torque on the shaft can be calculated.

However, the air gap between the probe and shaft will change continuously with the rotation of the shaft, due to mechanical errors, vibrations and other issues. The disturbance of the air gap will play a major role in the change of magnetic resistance, thus seriously affecting the measurement, because the magnetic permeability of air is much smaller than the shaft and the magnetic core. This paper gives a magnetic circuit model by considering the change of the air gap, as shown in expression (2):

$$\Phi = NIl\mu S + lc\mu cSc + 2d\mu aSa \qquad (2)$$

Φ is the magnetic flux, N is the turns density, I is the excitation current; l and lc is the effective length of the shaft and core, d is the air gap thickness; μ, μc and μa is the magnetic permeability of shaft, core and air. S, Sc and Sa is the effective cross-sectional area of the shaft, core and air gap.

A finite-element model was established for simulation, and a laser sensor which can measure the air gap thickness was added to the probe for experiments. According to expression (2), the fractional function was used to fit the data, and the results are as follows:

$$\Phi = p1d + p2d + q \qquad (3)$$

$p1=1.202$,$p2=1.395$,$q=0.8736$

The effect of fit can reach SSE = 8.136*10-6, RMES = 1.078*10-3. It can be concluded that the effect of air gap change on magnetic flux is consistent with formula (2).

But in the actual measurement process, the results are always lower than the voltage predicted by the model. Therefore, this study considered the influence of magnetic flux leakage in the magnetic circuit. As shown in Figure 1, not all magnetic flux can enter the shaft, some magnetic flux will leak through the air gap[2].

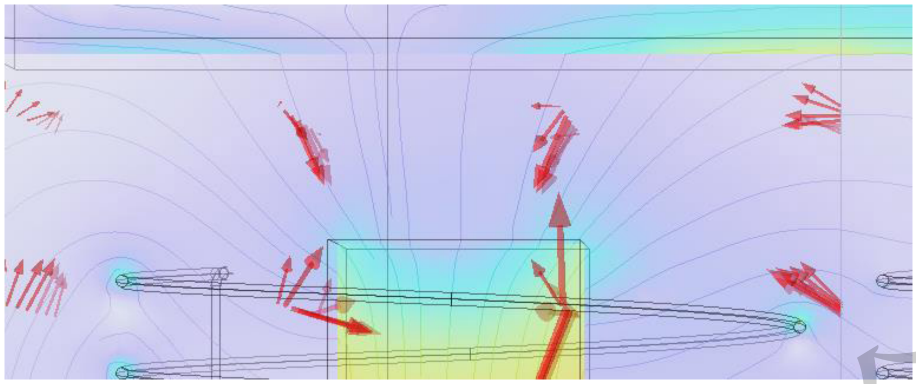

Figure 1 Magnetic flux distribution

Firstly, research what kind of magnetic flux could enter the shaft. Magnetic flux needs to satisfy the law of refraction without considering material anisotropy:

$\tan\alpha1\tan\alpha2= \mu1\mu2$ (4)

The magnetic permeability of the ferrite core and the shaft is much higher than air, when the magnetic flux is incident from air, it meets the following relationship due to $\mu1 \ll \mu2$.

$\alpha1=\arctan(\mu1\mu2 tan\alpha2) \approx 0°$, 当 $\alpha2 \neq 90°$ (5)

So, it can be approximated that magnetic flux can only pass through the interface from air when it is perpendicular to the surface of the medium[3]. Next, calculate the effective magnetic flux entering the shaft by Biot-Savart law. Based on the previous analysis, only the perpendicular component to the surface is considered:

$\phi efft= \mu0I4\pi\iint R+r\ cos\theta(r2 + R2+2rRcos\theta+ d2)322\pi r2\pi0rm0d\theta dr$(6)

Φefft represents effective magnetic flux, I is the current of the excitation coil, R is the radius of the coil, and r represents the planar distance between the measurement point and the center the coil, θ is the angle between the measuring point and the center of the coil. This integral is an elliptical integral, so use numerical integration for calculation, the fitting equation for the effective magnetic flux with respect to the air gap can be obtained as follows:

$\phi efft=a\ db+c$ (7)

$a= -0.00345, b=0.05463, c=0.004013$

The fitting effect can reach SSE=4.128*10-8 and RMSE=1.02*10-5. The magnetic flux can be revised according to this fitting formula, the theoretical calculation results can correspond well with the simulation and experimental results.

3 Conclusion

This article elaborates on the measurement principle of magnetoelastic sensors and provides the direct impact of the air gap by the magnetic circuit model, subsequently, a leakage flux model was proposed to revise the shortcomings of the model. The finite element simulation and measurement experiments were conducted to verify the correctness of above models. The application of the above two models can effectively improve measurement accuracy, repeatability, and response frequency.

References

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