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Design of Switchable Magnetic Wheel for Dry Storage Cask Inspection Robot

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1. Introduction

Robots that can climb vertical walls and hold on to the surface at any angles are required in many mission-critical applications in hazardous environments such as inspection of pipes and reactor vessels in nuclear power plant, welding in ship building, and inspection of casks storing spent fuel rods. To maintain the robot position on inclined surfaces, two mechanisms are typically used: pneumatic suction [1] or magnetic wheels [2]. In terms of size and the ability to maintain its position without power, a robot with magnetic wheels is preferable to the one with suction pads. For irregular ferromagnetic surfaces, magnetic wheels are the only option.

In this paper, we describe a new design of a magnetic wheel the attractive force of which can be switched on and off. For the purpose of design, a force model that relates the size of the permanent magnet (PM) and the attractive force is developed.

2. Magnetic Force Model

Shown in Figure 1 is the simplified structure of the magnetic wheel considered in this paper. It consists of two ferromagnetic disks joined by a PM. Optional flexible tire can increase traction force by providing higher friction coefficient and larger contact area. Althought the actual design of the wheel would become different from this simplified geometry, it is sufficient to show the force capacity as it contains the essential parts of a magnetic wheel. The first step in deriving the holding force model is to estimate the reluctance between the circumferential surface of the wheel and the floor. Previous research assumed that the flux lines between the wheel

In order to derive a force model, a coordinate system is defined as in Figure 2, where δ is the minimal distance between the wheel and the holding surface to account for the tire thickness, R is the radius of the wheel. The flux line at an arbitrary angle of θ would be a circular arc, the center of which lies on the x-axis. The radius of the arc is denoted as ρ. Using the geometric relations, the permeance of the air gap between the wheel and the surface as

$$P_g = 2\int_0^{\theta_m} \frac{\mu_0 \sin\theta d\theta}{\theta[1-\cos\theta+\delta/R]} \tag{1}$$

Since the wheel is three-dimensional, it is necessary to account for the side leakages which are substantial. In this paper, the force model estimates the side leakages using the effective air gap defined as

$$g_{\text{eff}} = \frac{2\mu_0 R\sin\theta_m}{P_g} \tag{2}$$

Then, the permeance for the side leakage can be approximated as

$$P_{\text{sl}} = \frac{2\mu_0 w}{\pi}\ln\left(1+\frac{\pi X}{2g_{\text{eff}}}\right) \tag{3}$$

where X is the extent outside of which the leakage flux is negligible. The total permeance of the air gap between the wheel and the surface can be obtained by summing (1) with the side leakage permeances. Using the magnetic circuit approach, the magnetomotive force (MMF) acting on the air gap can be written as

$$F_g = H_c l_m \frac{R_g}{2R_g + R_{pm}} \tag{4}$$

where H_c is the coercitivity of PM, l_m the length of PM, and R_{pm} the reluctance of PM. The attractive force can be obtained by integrating the Maxwell stress tensor

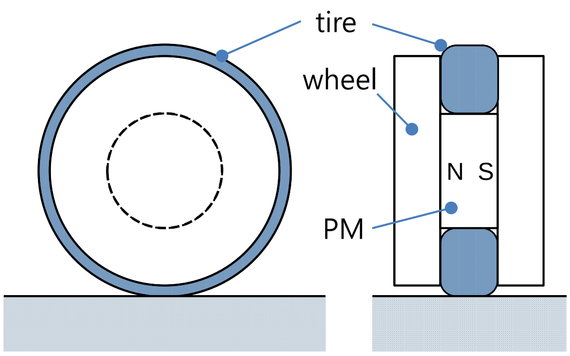

Fig. 1. Structure of a simplified magnetic wheel

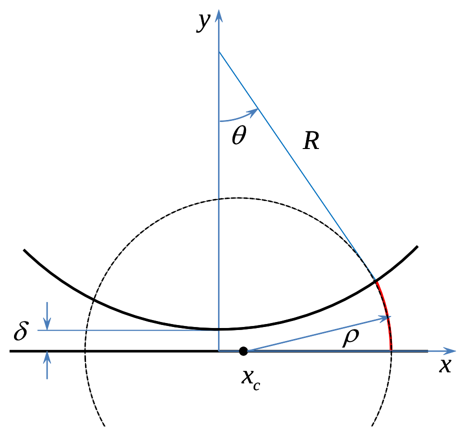

Fig. 2. Coordinates and the definitions of parameters

as

$$F = \frac{2\mu_0}{R}\int_0^{\theta_m} \frac{F_g^2 \sin^2\theta\cos\theta}{\theta^2[1-\cos\theta+\delta/R]^2} d\theta \qquad (5)$$

3. Validations

The force model in the previous section is numerically validated. Three-dimensional finite element analyses using MAXWELL3D are carried out and the results are compared with the predictions by the force model. The comparison is shown in Figure 3. The predictions generally match with the results of FEA. Since the trend and the range of the force with respect to the tire thickness agree well, the force model would be useful tool for the design of the magnetic wheel.

The concept of the magnetic switching is also validated using FEA. Figure 4 shows the magnetic wheels joined by a center PM. If the PM is aligned with the wheels, the attractive force is generated between the wheels and the surface. If the PM is rotated by 90 degrees, almost no magnetic force is generated. Using the force model above, we can determine the size of the PM in order to obtain the necessary holding force.

3. Conclusions

In this paper, we propose a model that estimates the holding force of a magnetic wheel adhering to a ferromagnetic surface. We also propose a design that the magnetic force can switched on and off. Currently, a mobile robot is being designed incorporating the switchable magnetic wheels. This robot will be used to carry sensors inspecting the dry casks storing the spent fuel rods.

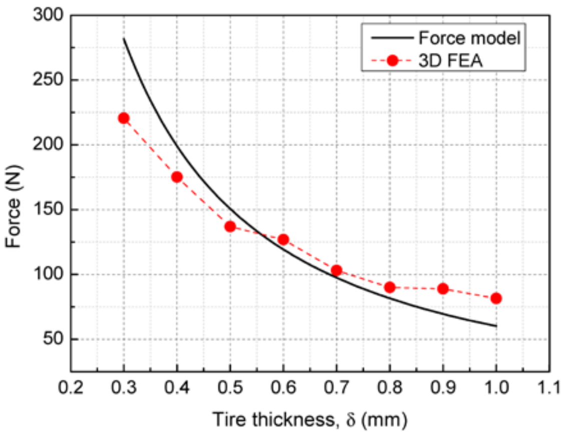

Fig. 3. Validation of the force model against 3D FEA

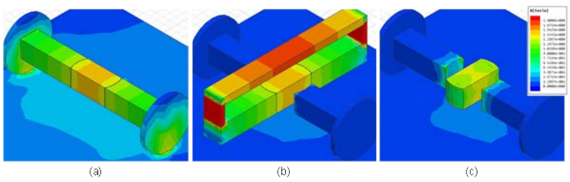

Fig. 4. Validation of the concept of magnetic switching

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