

Investigation of a Novel Power Trunk Locking System Using Electromagnetic Force of Permanent Magnet

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This article proposes a novel power trunk locking system using electromagnetic force to remove protrusion of conventional trunk locking system. The proposed system consists of contact plate, magnetic module, gear train, and cinching motor. The electromagnetic force from the permanent magnet in the magnetic module is applied to the contact plate attached to the trunk, thereby maintaining the holding force. In this article, firstly, the principle of a proposed magnetic trunk locking system is introduced. Subsequently, it is defined that the performance of the magnetic module should be evaluated in terms of the locking on force, locking off force, and cylindrical magnet rotational torque. The performance of the prototype magnetic module is analyzed using three-dimensional finite element analysis, and further verified by experimental tests. Finally, design variables for weight reduction of the magnetic module are selected, and weight reduction design is carried out.

Index Terms—Electromagnetic analysis, electromagnetic force, magnetic locking system, permanent magnets, vehicles.

I. INTRODUCTION

DUE to the high energy density and fast response, the magnetic locking systems have found applications in a number of areas [1]–[2]. Cho *et al.* proposed an efficient magnetic switch, using permanent magnet (PM), to remove the continuous consumption of electrical power in the conventional magnetic switch [1]. In [2], shape locking mechanism of surgical robots using electromagnetic force is introduced to improve surgical convenience.

So far, the power trunk locking systems for vehicles maintain holding force through a mechanical latch due to high reliability. However, the mechanical latch has an exposed holding protrusion. This protrusion may cause inconvenience to users and is susceptible to damage from user interaction.

In this article, a novel trunk locking system using electromagnetic force of PM is presented. By applying magnetic trunk locking system, it is possible to remove the protrusion and all devices are embedded into the vehicle. Meanwhile, replacing the conventional trunk locking system with a magnetic locking system results in an increase in weight, as shown in Fig. 1. Therefore, design of magnetic trunk locking system to reduce weight need to be conducted.

This article proposed a magnetic trunk locking system using magnetic module. Moreover, a design to reduce the weight of the magnetic module is conducted for decreasing the overall weight of the locking system. The following section explains the operating principle of the magnetic trunk locking system. In section III, the criterion is proposed to evaluate the performance of magnetic module in magnetic trunk locking system, and in section IV the performance of the prototype is analyzed using three-dimensional (3-D) finite element analysis (FEA). Furthermore, the experimental and numerical results are compared to verify the reliability of 3-D FEA. Finally, weight reduction design of magnetic module is conducted considering

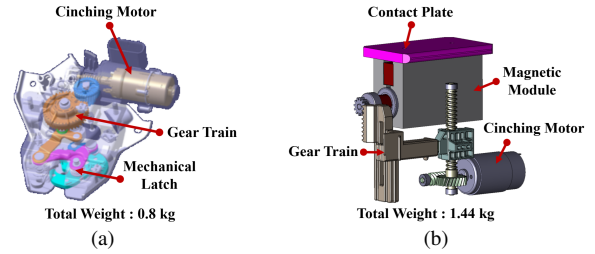


Fig. 1. Configurations of trunk locking system. (a) Locking system using mechanical latch. (b) Magnetic trunk locking system.

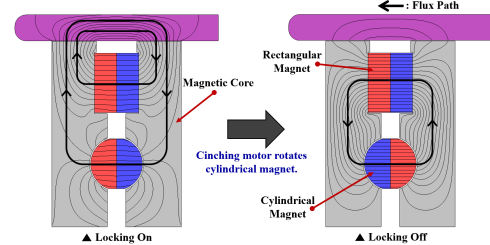


Fig. 2. Structure and operating principle of the magnetic trunk locking system in terms of magnetic module and contact plate.

three requirements defined in section III.

II. OPERATING PRINCIPLE OF A MAGNETIC TRUNK LOCKING SYSTEM

As shown in Fig. 1(b), the proposed magnetic locking system consists of contact plate, magnetic module, gear train, and cinching motor. The structure of the magnetic module is composed of magnetic core on both sides, with a rectangular and cylindrical magnets in between, as shown in Fig. 2. In the conventional system, the cinching motor contributed solely to the cinching operation. However, in the magnetic trunk locking system, it also functions to rotate the cylindrical magnet in magnetic module to change the locking on and off states.

A. Locking On Mechanism

As shown in Fig. 2, in the locking on state, the two magnets generate magnetic flux in the same direction, allowing the flux to flow toward the contact plate. This creates an electromagnetic force, securely pulling the contact plate.

B. Locking Off Mechanism

When the trunk needs to be opened, the cinching motor rotates the cylindrical magnet by 180 degrees to change to the locking off state. In the locking off state, the magnetic flux circulates between the two magnets, significantly reducing the flux flowing toward the contact plate. As a result, the electromagnetic force on the contact plate becomes negligible.

III. CRITERION FOR EVALUATING THE PERFORMANCE OF MAGNETIC MODULE

The performance of magnetic module can be evaluated in terms of locking on force, locking off force, and cylindrical magnet rotational torque (CMRT). In general, high locking on force, low locking off force, and low CMRT are required. Thus, the following constraints are set when air gap length between magnetic module and contact plate is 0.1 mm.

- 1) The locking on force required to hold the trunk should be greater than 2,200 N.
- 2) The locking off force should be less than 50 N, considering the actuator force that opens the trunk.
- 3) Considering the specification of the cinching motor, the CMRT should not exceed 1 Nm.

IV. PERFORMANCE OF THE PROTOTYPE MAGNETIC MODULE

A prototype is designed and manufactured considering aforementioned three constraints. Fig. 3 shows the performance of the prototype analyzed using 3-D FEA, and all three performance constraints are satisfied. Fig. 4 shows the manufactured prototype magnetic module and test setup. Table I lists the calculated and measured locking on force according to air gap length between magnetic module and contact plate. As shown, the calculated values are in good agreement with the measured values. Therefore, it is reliable to use the 3-D FEA for weight reduction design of magnetic module.

V. WEIGHT REDUCTION DESIGN

In this section, weight reduction design of magnetic module is conducted. First, the main design parameters are selected based on the magnetic equivalent circuit (MEC) of magnetic module. The MEC analysis identified that reducing leakage flux between magnetic cores on both sides and reluctance of the contact plate is necessary to increase the locking on force. The detailed MEC modelling method, parameters, and analysis results will be covered in the extended version.

Through the aforementioned design method, the weight reduction model is derived. As shown in Fig. 5, the thickness of the contact plate increased. To reduce leakage flux, the length of magnetic module decreased and the distance between magnetic cores increased. Moreover, the lower portions of the cores on both sides were chamfered to achieve additional

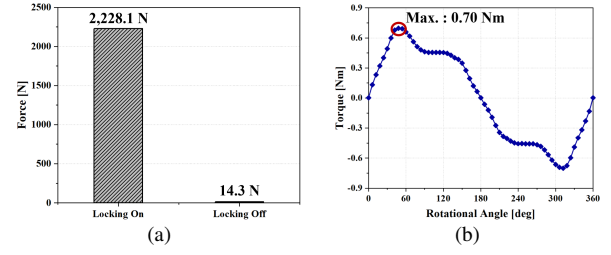


Fig. 3. Performance of prototype magnetic module. (a) Locking on/off force. (b) CMRT waveform.

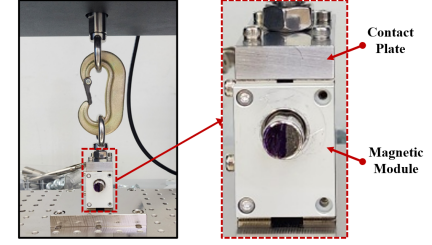


Fig. 4. Prototype and test setup to measure the locking on force.

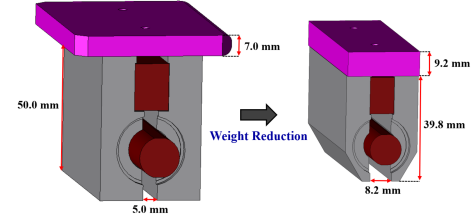


Fig. 5. Configuration of original model and weight reduction model.

TABLE I. Locking On Force of the Prototype Magnetic Module According to Air Gap Length

Air gap length	Calculated	Measured	Error
0.1 mm	2,228.1 N	2,301.6 N	3.2 %
0.2 mm	2,039.2 N	2,190.8 N	6.9 %
0.3 mm	1,860.0 N	1,733.8 N	7.3 %

TABLE II. Main Performance of Two Models

Item	Original model	Weight reduction model
Weight	1.20 kg	0.71 kg
Locking on force	2,228.1 N	2,231.8 N
Locking off force	14.3 N	49.7 N
CMRT (max.)	0.70 Nm	0.84 Nm

weight reduction, as these regions carry negligible magnetic flux. As listed in Table II, the weight of magnetic module decreased 40.8% satisfying all three constraints. The detailed weight reduction design process will be explained in the extended version.

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