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Integrated Design of In-Wheel Motor System on Rear Wheels for Small Electric Vehicle

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Abstract

Generally, In-Wheel motor system consists of suspension, steering, electric motor, friction brake, and wheel and varies with the combination structure of each component. However, the key point of In-Wheel motor system to be applied in small electric vehicle is the integration capability to meet the requirements such as wheel space, power performance, strength of components and so on. This paper describes integration methodology for In-Wheel motor system on the rear axle with the consideration of the restricted wheel space and unsprung mass. In addition, optimization of the motor housing is performed to improve mass and strength of the In-Wheel motor housing according to the test specification of weight transfer from the tire patch. It is found from the results that the prototype In-Wheel motor system meets the vehicle performances and strength requirements.

Keywords: In-Wheel Motor, Electric Propulsion, Electric Vehicle, Design of Experiment

1 Introduction

Recently, the major automakers put their efforts on development of electric propulsion system such as EV(electric vehicle), HEV(hybrid electric vehicle) including Plug-in HEV and FCV(fuel cell vehicle). The key drivers can be shortened as 1) CAFE regulations - 35 fleet mpg by 2020, could be higher, 2) Government incentives and subsidies for EVs, free parking for EVs by many cities, exemption from emission certification by some states, HOV(high-occupancy vehicle) lane driving exemption for EVs with a single occupant, 3) Technological innovation and economies of scale have driven significant reduction in Li-Ion batteries, and 4) Growth in charging infrastructure and new business opportunities[1].

The application scenario of electric propulsion can be divided into two categories. The first is conservative and cost effective system that a single motor is mounted on the center of the chassis by eliminating internal combustion engine and the power from the motor is transmitted to the wheels through the drivetrain such as the transmission, the differential, the drive shaft and the universal joints. The second category is an innovative system that a number of In-Wheel motors are installed in each wheel and the power from the motors are transmitted to the wheels without any shafts[2]. With In-Wheel hardware characteristics, the In-Wheel motor vehicles have the merits of more interior space, design freedom, lowered center of gravity and weight balance and have greater fuel economy and vehicle stability since the drive and brake torque at each wheel can be controlled independently via yaw moment control using the creation of torque differences between the left and right wheels[3].

Many advanced research group have designed In-Wheel motor installation into EVs such as KAZ[4], Luciole[5] and IZA[6] in Japan and TM4 in Canada[7]. However, it is still difficult to install In-Wheel motor system into the restricted wheel space, especially for front drive wheel, by considering the package interference with brake, steering and suspension structure. Therefore, high level of integrated design is necessary to adopt the In-Wheel system to electric propulsion vehicle by considering the restricted wheel space and minimized unsprung mass.

In this paper, integrated design of In-Wheel motor system on the rear axle for small electric vehicle is investigated. In addition, optimization of the motor housing is performed to reduce mass and improve strength of the In-Wheel motor housing according to the test specification of weight transfer from the tire patch.

2 System Design

Figure 1 shows the configuration of the prototype In-Wheel motor system on rear wheels for small EV. The unique parts of the proposed In-Wheel motor system consist of torsion beam suspension, motor, planetary gear as a reducer, drum brake, hub bearing and its integration parts. Other parts of the vehicle such as front motor, high voltage battery, power electronics, and mechanical devices which is commonly used parts of EV have not been shown.

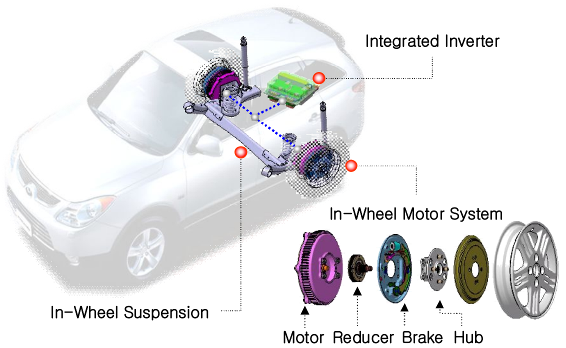


Figure 1: Configuration of In-Wheel system

As a rear suspension, torsion beam axle is used, which make it easier for In-Wheel motor to be attached without package interference. An integrated inverter which controls the motor torque is placed under the luggage room.
Figure 2 shows assembly aspect of the prototype In-Wheel system in a wheel corner.

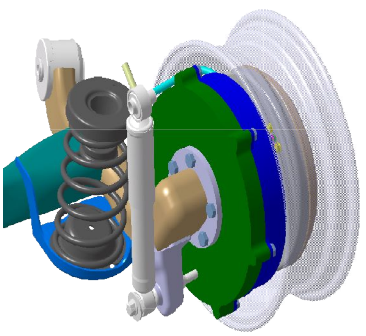


Figure 2: Assembly aspect in a wheel corner

Planetary gear set is adopted as a reducer having 4.0 reduction ratio and is mounted at the hollow space of In-Wheel motor housing. As a friction brake, drum brake is used with reduced width of friction pad and enlarged diameter of disk rotor. In the inner space of drum brake, hub and bearing is located. Fixed part of hub is mounted at the side of motor housing and rotational part of hub transmits the motor torque to the wheel.
These integrated design methods enable minimization of the width of In-Wheel system and improvement of the system performance such as strength of reducer, durability of torsion beam axle and reduction of unsprung mass.
Specifications of the prototype In-Wheel system are listed in Table 1.

Table 1: Specifications of In-Wheel system

Specification		Unit	Value
Vehicle	Curb weight	kg	1186
	Max. speed	km/h	130
	Tire size	-	175/60R14
	Rated voltage	Vdc	330
Motor	Type	-	PMSM
	Max. output	kW	17
	Max. torque	Nm	130
	Max. speed	rpm	5000
Reducer	Type	-	planetary gear
	Reduction ratio	-	4.0

2.1 In-Wheel Motor

Since In-Wheel motor should be mounted in each wheel, the size of the motor is very stringent. It should be a thin one, that is to say, short to the axle direction and radius is limited by the size of the tire radius. Among all kinds of electric motor utilized on electric vehicles, the permanent magnet synchronous motor (PMSM) has the smallest size [8].
In the mechanical design of In-Wheel motor, there are too much requirements regarding assembly procedure of each part, harness routing, bearing, heat transfer and so on. In order to ensure the clearance between rotor and stator of In-Wheel motor, a double row thrust ball bearing is used to support complex loads.
In the electro-magnetic design of In-Wheel motor, parametric optimization is carried out to meet the required power, size and mass.
Cross section of prototype In-Wheel motor is shown in Fig. 3.

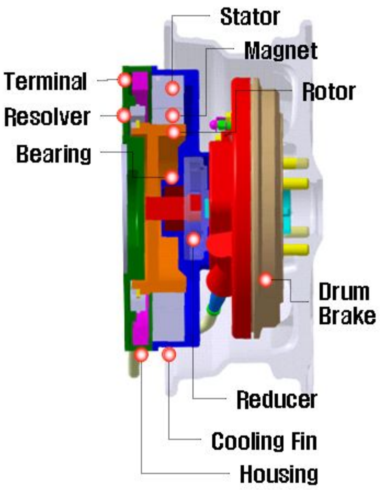


Figure 3: Cross section of In-Wheel motor

Figure 4-5 show the T-N curve and efficiency map of In-Wheel motor under development in this study.

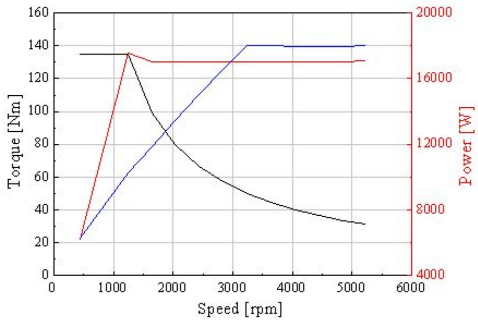


Figure 4: Characteristic map of In-Wheel motor

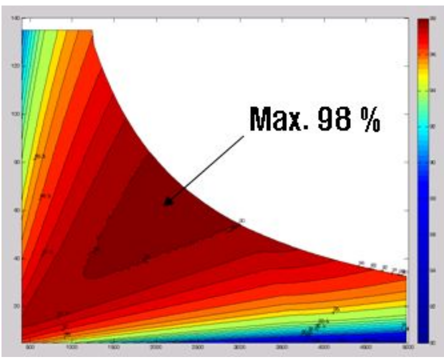


Figure 5: Efficiency map of In-Wheel motor

2.2 Inverter

Left and right motors are controlled by an IGBT based inverter. The switching logic of the inverter is synthesized by dual closed-loop control system. The power IGBT and controllers are integrated into an inverter. The integrated inverter is capable of driving left and right motors independently in both the forward and the reverse directions. Regenerative braking is also provided by the inverter. Composition of integrated inverter is shown in Fig. 6.

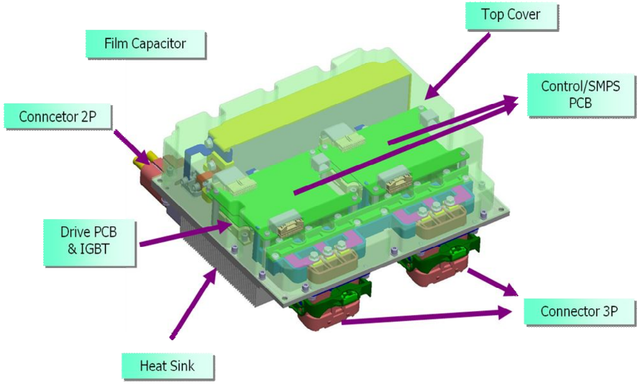


Figure 6: Composition of integrated inverter

2.3 Reducer

The type and reduction ratio of reducer is one of the key components to make a decision on the structure of In-Wheel system between a single shaft type and offset type, the size and mass of motor, strength of each part, durability of suspension, and finally vehicle performance. Therefore, it is important to select the type of reducer by considering the vehicle grade, wheel size and target specifications. With the basis of the requirements of the small EV equipped with torsion beam axle and 14 inch wheel, interior planetary gear set is used.

As shown in Fig. 7, a reducer designed as one assembly is located in the hollow space of the motor and mounted with 6 bolts, by which maintainability improves potentially.

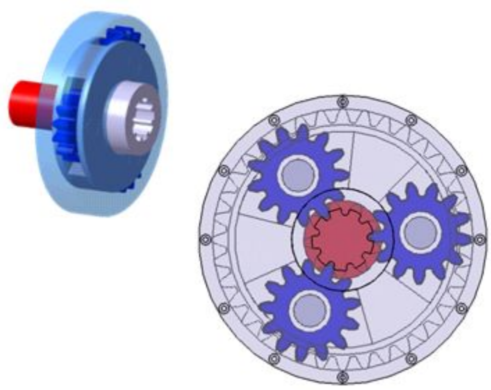


Figure 7: Schematic diagram of a reducer

2.4 Brake

In order to reduce the axial width of In-Wheel system, a drum brake with reduced width of friction pad and enlarged diameter of disk rotor is designed and a hub bearing is located below the drum. Schematic diagram of prototype drum brake is shown in Fig. 8.

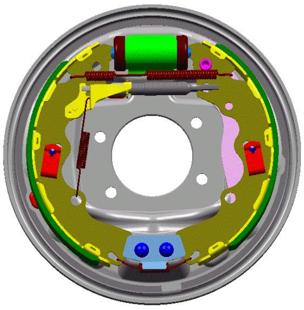


Figure 8: Schematic diagram of drum brake

3 Design Optimization

To avoid detrimental effects of increased unsprung mass on driving stability and ride comfort of the vehicle, In-Wheel motor, which occupies the largest amount in In-Wheel system, should be designed as lightweight as possible.

3.1 Optimization of Motor Housing

In optimization of the motor housing, mass reduction and strength improvement have to be taken into account simultaneously. The objective is minimization of peak stress and mass of the motor housing. The design parameters are listed as below,

Objectives: Minimize (Stress × Mass)

Noise variables:

- Weight transfer from the tire patch to inner side
- Weight transfer from the tire patch to outer side
- Weight transfer from the wheel center to upper

Control variables: Name and level are listed in Table 2.

Table 2: Control variables of the motor housing

	Level 1	Level 2	Level 3
A. Thickness	6.5 mm	9 mm	12 mm
B. Front curvature	1	8	15
C. Rear curvature	1	4	8
D. Number of Rib	2	4	6

$L_9(3^4)$ orthogonal array has been constructed with 4 control variables of 3 levels. FEM stress analysis results are listed in Table 3.

Table 3: Orthogonal array and analysis results

	A	B	C	D	Inner	Outer	Upper	S/N (dB)
L1	1	1	1	1	186.8	183.8	125.5	**-44.5**
L2	1	2	2	2	178.8	173.8	126.0	-44.2
L3	1	3	3	3	172.4	166.3	123.2	**-43.8**
L4	2	1	2	3	181.4	176.4	128.2	-44.3
L5	2	2	3	1	174.4	168.2	124.6	-43.9
L6	2	3	1	2	228.8	226.3	166.5	-46.4
L7	3	1	3	2	186.2	191.2	127.3	-44.7
L8	3	2	1	3	236.5	232.1	161.7	-46. 6
L9	3	3	2	1	219.7	191.2	155.3	-45.6

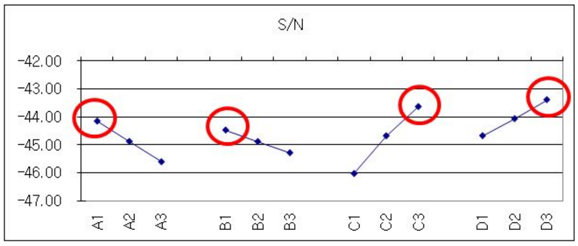


Figure 9: Response plots for design variables

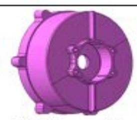
NO.	A	B	C	D	S/N (dB)	Gain
 Initial model	1	1	1	1	-44.49	-
 1st Optimum	1	3	3	3	-43.84	0.65 dB (7.2% ▲)
 Final Optimum	1	1	3	3	-41.98	2.51 dB (25.2% ▲)

Figure 10: Analysis results for optimal combination

From the results in Fig.9-10, optimal combination of control variables is derived. The final optimum of the motor housing shows 25.2% improved objective function value, compared with the initial model.

4 System Analysis

In this chapter, strength and endurance tests for hub and torsion beam axle are performed using FEM software. In addition, digital package analysis is carried out to avoid package interference.

4.1 Strength and Endurance Test

In order to ensure the strength of hub and torsion beam axle, FEM analysis is performed according to the test specification. The test condition of hub is defined as weight transfer traveling in 0.6g cornering.
Figure 11 shows the analysis results.

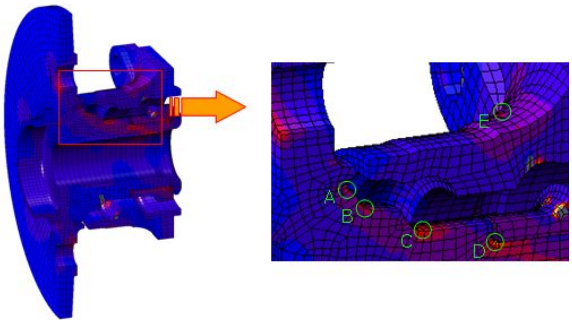


Figure 11: Analysis results for hub

The strength of hub is evaluated by the deformation angle of the flange and the stress at the weak point. From the analysis results, maximum deformation angle reaches 85% to the fail value and the Von-Mises stress of A, B, C, D, and E point are below the allowable level.
The test condition of torsion beam axle is the roll endurance with the input of +80mm ~ -80mm displacement in the wheel center.
From the analysis results in Fig. 12, our prototype torsion beam axle satisfies requirements but reinforcements will be placed furthermore.

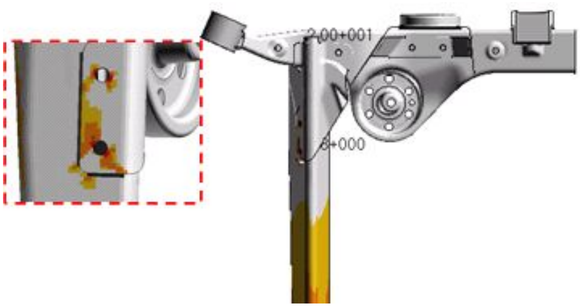


Figure 12: Analysis results for torsion beam axle

4.2 Package Analysis

In order to avoid package interference between the side member and nearest point of the In-Wheel system, digital package analysis is performed under the input of wheel stroke range from +100mm to -70 mm.

From the analysis results in Fig. 13, the nearest distance is about 24 mm between the side member and the spindle bracket.

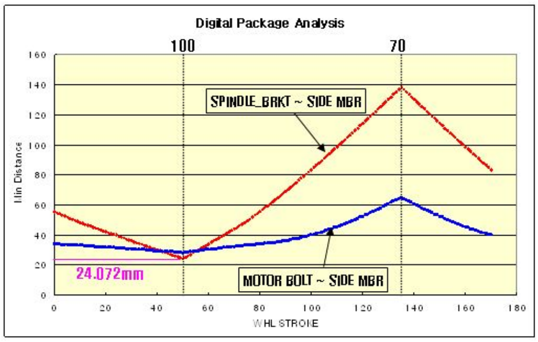


Figure 13: Analysis results of package

5 Conclusion

In this paper, integrated design methods enable minimization of the width of In-Wheel system and improvement of the system performance such as strength of reducer, durability of torsion beam axle and reduction of unsprung mass. In addition, In-Wheel motor is improved by the optimization procedure at the area of mass reduction and strength improvement.
It is found that the reducer is the one of the key component to make a decision on the structure of In-Wheel system, the size and mass of motor, strength of each part, durability of suspension, and finally vehicle performance. Therefore, it is important to select the best reducer by considering the vehicle grade, wheel size and target specifications.
It is found from the test results that the strength of hub and the endurance of torsion beam axle satisfy the test specifications. In addition, the concern of package interference can be removed by the package analysis.

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