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Development of Noise and Vibration Reduction Technology for In-Wheel Motor Vehicles

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ABSTRACT: Based on the serious problem of global warming, electric vehicles are focused on because of no greenhouse gas emissions. In-wheel motor (IWM) systems, where the drive motor is installed into wheel, is one of the major electric vehicle drive systems. IWM vehicles have advantage for dynamic performance by four-wheel independent control and flexible interior layout, but they also have several problems for mass-production. The cabin noise is one of the serious issues, because of vibration that occurs due to the unit being directly installed into the suspension. Therefore, reducing the vibration is important for IWM units with consideration of the vehicle's transmission characteristics. This paper describes countermeasures against vibration sources by the motor current control and against the vibration transfer through the trailing arm.

KEY WORDS: electric vehicle, power electronics, motor, powertrain, noise, vibration, in-wheel motor

1. INTRODUCTION

Electric vehicles are known as one of the few options that do not output greenhouse gases during driving. In addition, electric vehicle's motors can flexibly be installed into vehicle, therefore various drive systems have been developed. One of them is in-wheel motor (IWM) system, where the motor is installed into each wheel. Compared to conventional engine vehicles and HEV vehicles, IWM vehicles have advantages such as greater flexibility in their interior layout, improved vehicle dynamic performance through independent control of the four wheels, and the ability to stabilize the posture of the vehicle sprung mass [(1)]. In addition, IWM vehicles have high rigidity from the motor shaft to the wheel shaft, which can be expected to improve TRC/ABS performance on snowy roads through highly responsive motor driving force control. On the other hand, as shown in Table 1, there are several problems for mass-production vehicles. Among them, this paper focuses on NV, and examines countermeasures to reduce in-vehicle noise using a prototype-vehicle.

Table 1 Major issues for mass production

Built into the wheel	interference with brake, suspension, wheel
Noise and Vibration	in-vehicle noise and vibration
Heat resistance	heat received from brake and limitation of cooling system
Reliability	durability in unsprung high G environment
High voltage safety	exposure of high voltage parts when derailing
Mass	uncomfortable ride due to increased unsprung weight

2. IWM UNIT

Fig. 1 shows the external view of the IWM unit equipped with the prototype-vehicle and its specification table. The prototype-vehicle is based on a BEV vehicle and uses only the IWM units built into the four wheels as a power source. The IWM unit is built into the 18-inch wheel and the 8-pole pair motor torque is amplified through a reduction gear.

system voltage	[V]	500
maximum motor torque	[Nm]	331
maximum motor power	[kW]	75
maximum motor speed	[rpm]	5000
reduction ratio	[-]	3.69
front suspension		strut
rear suspension		trailing arm

Fig. 1 Specification of IWM unit

3. NV ISSUES FOR IWM VEHICLES

Fig. 2 shows the mechanism of IWM vehicle vibration. The vibration occurs because the IWM is built into the suspension system which is made of rigid parts, and amplifies the transmission of vibration to the body. Therefore, it is crucial to solve these issues such as reducing the IWM vibration and reducing the body vibration based on body-to-IWM transmission characteristics. Table 2 shows the NV issues for IWM vehicles. Among these issues, this report refers to the study of the in-vehicle noise during driving and regeneration, which is most relevant to the product competitiveness.

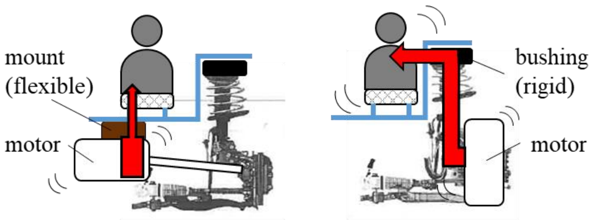


Fig. 2 Vibration mechanism of IWM system

Table 2 NV issues for IWM vehicles

category		issues	sensory level (1 2 3 4 5; bad – good)
noise	inside-vehicle	dive and regeneration sounds	1
		gear noise	3
		gear rattling noise	1
		beat noise	2
	outside-vehicle	radiation sound from IWM unit due to motor noise	2
vibration	steering wheel	vibration transmitted through tie rod end	2
	harshness	sound pressure when passing a step	1
			acceptable

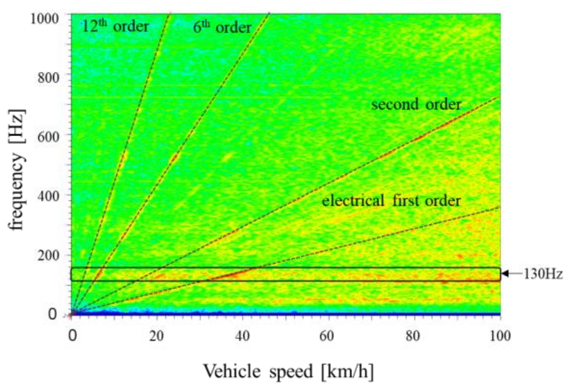


Fig. 3 Results of frequency analysis of in-vehicle noises in the IWM vehicle

Fig. 3 shows the results of frequency analysis of the in-vehicle noise when the vehicle was accelerating from 0 km/h to 100 km/h at 0.05G. The driving torque of the four wheels during acceleration is equalized. First, second, 6th, and 12th order forces are observed when arranged by electrical excitation order. Furthermore, focusing on the frequency, it was found that there is a resonance frequency near 130Hz. This report explains the reduction methods of these four forces, and the 130Hz resonance.

4. FACTORS AND COUNTERMEASURES FOR THE IN-VEHICLE NOISE OF EACH ELECTRCAL ORDER AND 130Hz RESONANCE

4.1. The electrical first order in-vehicle noise

4.1.1. Factor analysis of the electrical first order in-vehicle noise

In order to identify the cause of the electrical first order in-vehicle noise, we analyzed frequency of the q-axis current in motor vector control and three-phase current. As shown in Fig. 4, the q-axis current is oscillating with the electrical first order cycle, and only one of the three-phase currents is offset. Therefore, the cause was presumed to be the current sensor's offset.

The current sensors are installed at the three phases inside the inverter. The sensor records a voltage of 0A when the inverter is shutting down. Furthermore, there are two sensor circuits, one for low resolution and one for high resolution, which are switched according to the driving conditions as shown in Fig. 5.

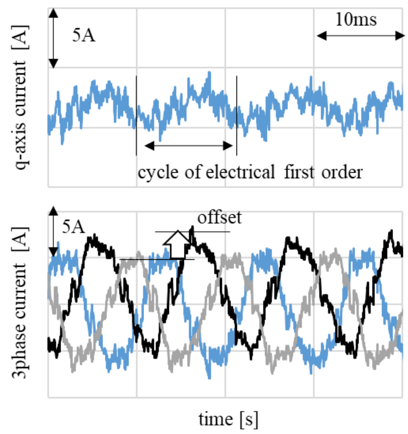


Fig. 4 Results of frequency analysis of q-axis current and 3phase current

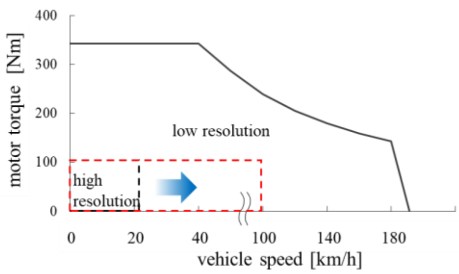


Fig. 5 Areas of use for low-resolution mode and high-resolution mode in the current sensor

The vehicle noise strongly appeared at the speed of 20 km/h or higher during test, therefore the cause of noise could be that the sensor resolution was too low and the voltage is offset at 0A.

4.1.2. Countermeasures and effect of the electrical first order in-vehicle noise

In order to improve the sensor resolution, we expanded the current sensor's high-resolution usage range to high vehicle speeds, as shown in Fig. 5. Fig. 6 shows the effect. Using this countermeasure, the electrical first order noise was reduced by a maximum of 8dB inside the vehicle.

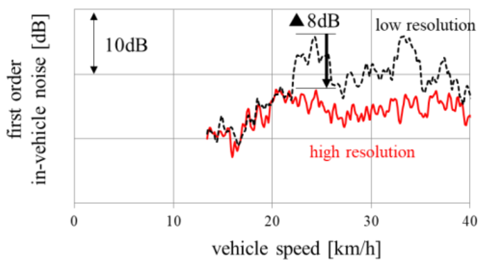


Fig. 6 Effect of reducing the electrical first order in-vehicle noise by high resolution mode

4.2. The electrical second order in-vehicle noise

4.2.1. Factor analysis of the electrical second order in-vehicle noise

Since there is no electrical second order vibration in the q-axis current and IWM unit vibration was confirmed even when the inverter was not driven, it was presumed that the electrical second order in-vehicle noise was caused by the motor hardware.

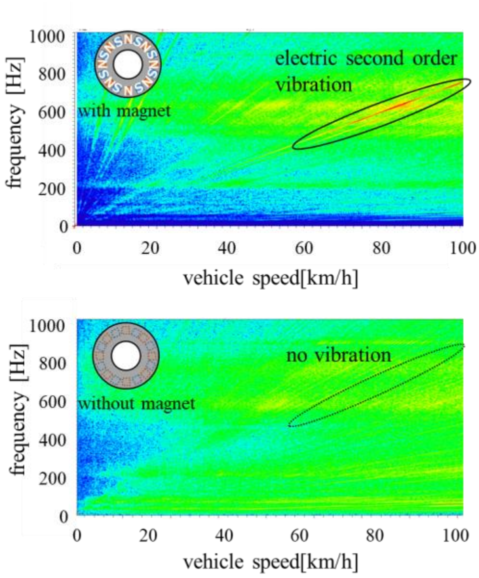


Fig. 7 Results of frequency analysis of IWM unit vibration when the inverter is shut down

Therefore, as shown in Fig. 7, IWM unit vibration was measured using a magnet-less rotor. Since the electrical second order vibration disappeared, it was found that the stator vibration due to the magnetic attraction force was the cause.

Since the IWM is built into a limited space, it is important to improve the torque density, and the motor used in this study has a larger amount of magnets than a normal motor. Therefore, the stator vibration increases because of the increase in magnetic attraction force.

4.2.2. Countermeasures and effect of the electrical second order in-vehicle noise

In order to reduce the stator vibration due to the attraction force of the magnet, as shown in Fig. 8, we took measures to increase the d-axis current, which is the direction of attraction of the magnet, by approximately 30A by advancing the phase angle of the current.

Using this countermeasure, the electrical second order in-vehicle noise was reduced by a maximum of 8dB. This countermeasure increases the motor copper loss, but the increase of electric power consumption as a vehicle was relatively small at only 0.7%.

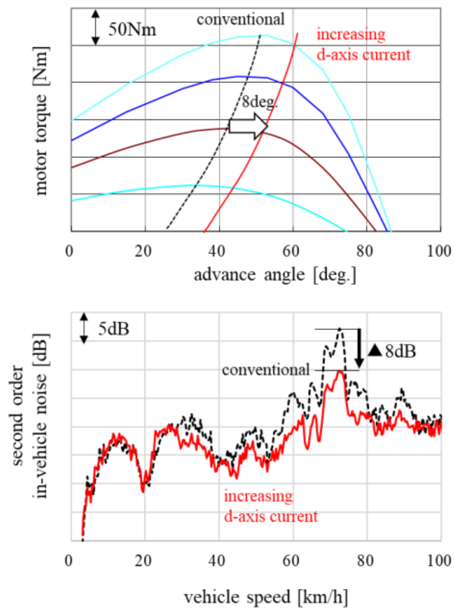


Fig. 8 Effect of reducing the electrical second order in-vehicle noise by increasing d-axis current

4.3. The electrical 6th order in-vehicle noise

4.3.1. Factor analysis of the electrical 6th order in-vehicle noise

In order to identify the cause of the electrical 6th order in-vehicle noise, we analyzed the frequency of the q-axis current and the three-phase current. As shown in Fig. 9, the q-axis current is oscillating with the electrical 6th order frequency and with the timing of the zero-crossing of the three-phase current. Therefore, the cause was presumed to be the dead time of the inverter.

Dead time is the time during which the upper and lower arm switches of the inverter are turned off at the same time in order to prevent short-circuit current. Due to this dead time, the apparent voltage decreases when the current is positive and increases when the current is negative. Therefore, a voltage change occurs near the current value zero at which the positive and negative sign is switched, and the current stays near 0A.

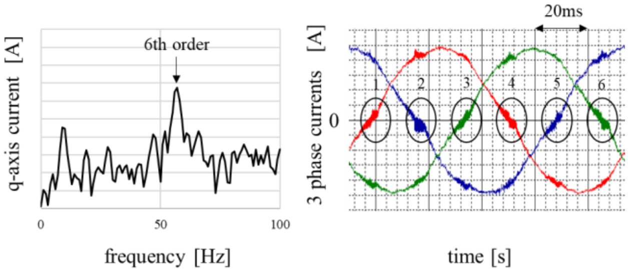


Fig. 9 Results of frequency analysis of q-axis current and 3phase current

4.3.2. Countermeasures and effect of the electrical 6th order in-vehicle noise

In order to reduce the current stagnation due to dead time, as shown in Fig. 10, voltage compensation control was performed to increase the voltage during positive current and decrease the voltage during negative current. Fig. 11 shows the effect. It can be seen that the stagnation near the current value of zero can be suppressed by the control. Using this control, the electrical 6th order noise was reduced by a maximum of 15dB inside the vehicle.

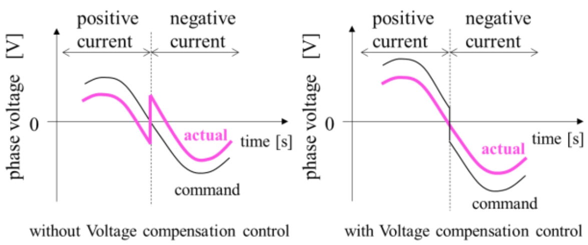
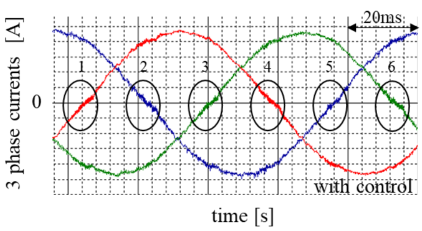


Fig. 10 Voltage compensation control to suppress current stagnation



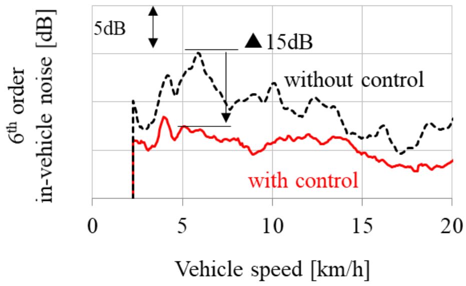


Fig. 11 Effect of reducing the electrical 6th order in-vehicle noise by voltage compensation control

4.4. The electrical 12th order in-vehicle noise

4.4.1. Factor analysis of the electrical 12th order in-vehicle noise

The cause of the electrical 12th order in-vehicle noise is the torque ripple of the motor. A lot of research and development has been done to reduce torque ripple, and there are countermeasures by motor hardware such as improvement of magnet orientation and magnetization direction and countermeasures by motor current control.

In HEV vehicles, vibration is reduced by adding current to the motor that cancels torque ripple, especially in the low vehicle speed range, and the same control is implemented in this prototype vehicle.

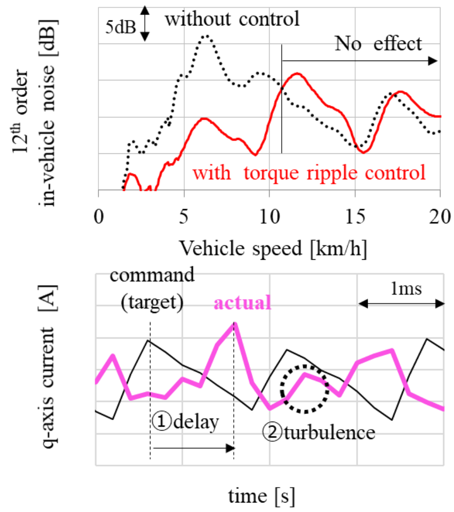


Fig. 12 Effect of torque ripple control and difference Command current and actual current at 12km/h in the torque ripple control

On the other hand, as shown in Fig. 12, when the vehicle speed is 10 km/h or more, the effect of torque ripple control is small. The current analysis at a vehicle speed of 12 km/h shows that the actual current is delayed behind the command current, and the shape of the actual current is distorted. This is because the delay in the calculation speed and FB control increased as the motor speed increased, and the current disturbance increased due to the increase in the back electromotive force applied to the motor.

4.4.2. Countermeasures and effect of the electrical 12th order in-vehicle noise

Fig. 13 shows the details of the countermeasures. Countermeasures against factors that delay the actual current are implemented by phase correction control that advances the command current, and countermeasures against factors that disturb the shape are implemented by adding back electromotive force (BEF) to the FF term of the command voltage.

Fig. 14 shows the effect. It can be seen that the target current shape can be maintained without delay with respect to the command current by taking countermeasures. Using this control, it was possible to reduce the noise in the car by a maximum of 8 dB at speeds up to around 20 km/h.

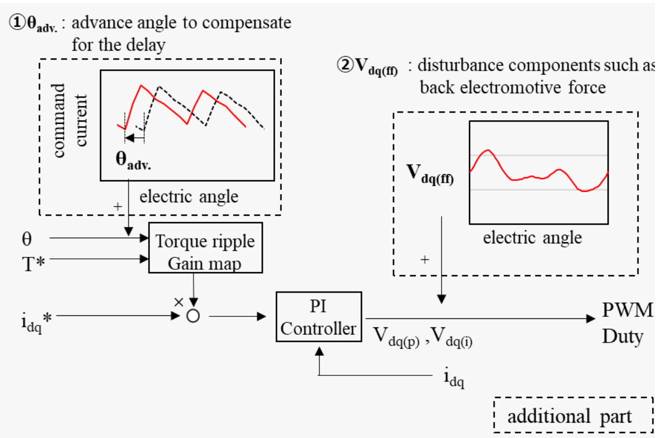


Fig. 13 Phase correction control and BEF FF control

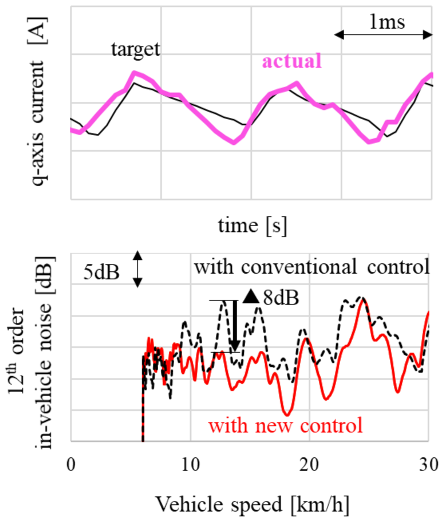


Fig. 14 Effect of reducing the electrical 12th order in-vehicle noise by phase correction control and BEF FF control

4.5. The 130Hz resonance

4.5.1. Identification of resonance parts at 130Hz

In order to identify the vibration path of 130Hz, operational transfer path analysis was conducted that allows us to grasp the vibration contribution of each part when the vibration of the IWM unit passes through the suspension system and the body and becomes the noise inside the vehicle. In this study, the in-vehicle noise was particularly loud from the rear wheels, so we attached an accelerometer to the suspension system of the rear wheels shown in Fig. 15 and performed the analysis under the same running conditions as in Fig. 3. As shown in Fig. 16, a large contribution was found from the trailing arm around 130Hz.

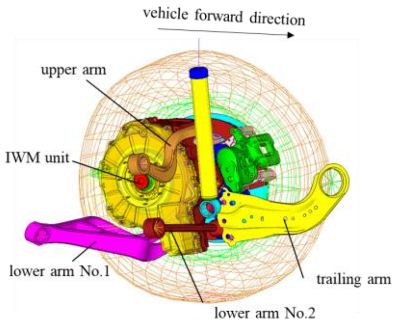


Fig. 15 IWM unit and rear suspension system

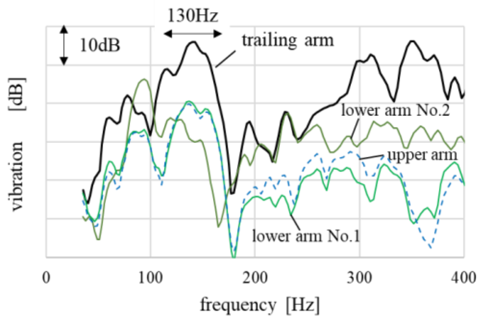


Fig. 16 Results of transfer path analysis of the rear suspension system

4.5.2. Resonance mode analysis at 130Hz and countermeasures

Focusing on the trailing arm, we performed resonance mode analysis in the 130Hz band by CAE. As shown in Fig. 17, it was confirmed that the mode in which the IWM unit vibrates in the rotational direction and the trailing arm connected to it applies vertical force to the body. As shown in Fig. 18, two bushings were added to the joint between the IWM unit and the trailing arm to suppress the-force transmission. The effect is shown in Fig. 19. By using this countermeasure, it was possible to reduce the in-vehicle noise around 130Hz in the 12th electrical order by a maximum of 5dB.

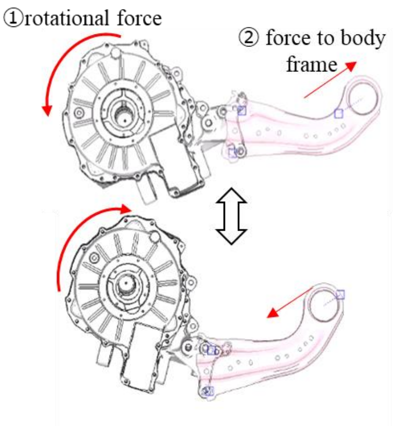


Fig. 17 Resonance mode at 130Hz in IWM unit and trailing arm

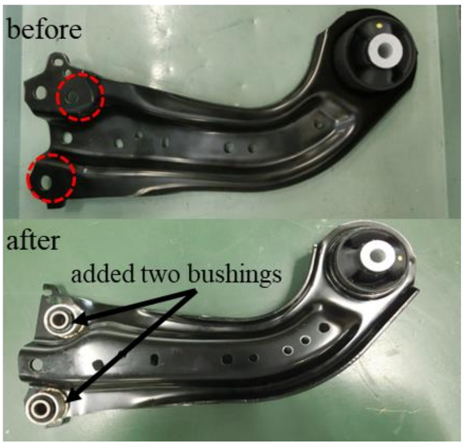


Fig. 18 Adding two bushings to the trailing arm

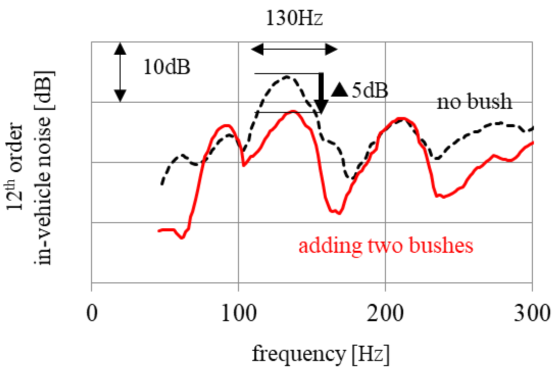


Fig. 19 Effect of reducing the electrical 12th order in-vehicle noise around 130Hz by adding two bushings

5. CONCLUSION

The following conclusions were obtained from this study.

[1] In order to improve the offset of the current sensor, the high resolution area of the sensor was expanded. Using this countermeasure, the electrical first order in-vehicle noise was reduced by a maximum of 8dB.

[2] In order to reduce the stator vibration due to the attraction force of the magnets, the d-axis current has been increased. Using this countermeasure, the electrical second order in-vehicle noise was reduced by a maximum of 8dB.

[3] In order to reduce the current stagnation due to dead time, the voltage compensation control was performed to increase the voltage during positive current and decrease the voltage during negative current. Using this control, the electrical 6th order noise was reduced maximum 15dB inside the vehicle.

[4] In order to improve the current delay and turbulence due to the calculation speed and the back electromotive force, the Phase correction control and BEF FF control was performed. Using this control, the electrical 12th order noise was reduced by a maximum of 8dB inside the vehicle.

[5] In order to suppress the transmitted force from the IWM unit arm, two bushings were added to the trailing arm. Using this countermeasure, the in-vehicle noise around 130Hz in the electrical 12th order was reduced by a maximum of 5dB.

In the future, the remaining NV issues such as harshness and vehicle exterior noise will be studied.

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