Improvement of Vehicle Vibration while Driving Using Motor Integral CTBA

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Received on May 22, 2018

ABSTRACT: With driving parts including a motor equipped inside each wheel, in-wheel motor system drives wheels directly. If the motor is combined with CTBA, the drive system and the suspension system are modularized in a simple structure, expanding inside space and improving cost competitiveness. Moreover, as a controller of driving power and braking force of the motor, it also enhances ride quality and handling by controlling the pitch and yaw of the vehicle. However, in-wheel system directly related to the sash is disadvantageous to vibration isolation of the motor/reduction gear. The purpose of this research is to identify the causes of 1st. order vibration in vehicles with motor integral CTBA and suggest countermeasures to this problem.

KEY WORDS: vibration, noise, and ride comfort, body vibration while driving, motor integral CTBA, bush, soft foot, in-wheel motor [B3]

1. Introduction

With driving parts including a motor equipped inside each wheel, in-wheel motor system drives wheels directly. It enables control of the independent torque of each wheel, optimal driving and energy regeneration, and has high efficiency. Being an electrical driving system, it can be applied to any eco-friendly vehicles with a high-voltage system. As the technology increases advantages of eco-friendly vehicles, it is expected to be applied to different vehicle types with various concepts, rather than as a simplified development of a single concept. For instance, if in-wheel motor system is applied to the rear wheels as auxiliary power to an FF vehicle whose primary power is the engine, both fuel efficiency and 4WD performance can be boosted at the same time by comparatively simply changing the powertrain.

As for the types of the concept, there is a type that the driving motor is directly connected to the chassis, a type that the reduction gear and the motor are integrated or a type that the chassis and the motor are integrated as shown in Fig 1.

One of the rear-wheel suspension system types where the trailing arm and the torsion beam are combined, CTBA (Coupled Torsion Beam Axle) is a suspension system that implements the function with a comparatively simple structure.

If the motor is combined with CTBA, the drive system and the suspension system are modularized in a simple structure, expanding inside space of cabin and improving cost competitiveness. Moreover, as a motor integral CTBA applied to the rear wheels maintains a simple vehicle package, it makes it easy to expand vehicle types and reduces geometric changes in the suspension system. The controller of driving power and braking force of the motor, it also enhances negative elements of CTBA-type ride and handling by controlling the pitch and yaw of the vehicle.

Unlike the general drive system that is mounted on the engine room as an insulator, however, the in-wheel motor system, which is directly connected to the chassis, is disadvantageous to vibration isolation of the motor/reduction gear. Since the CTBA structure has a simpler suspension system and transfer path compared to multi-links, tuning targets are limited to bushes equipped in trailing arm/spring/damper; as there are few variables, it is hard to optimize 1). As for the structural characteristics, since vibration from the drive system and road surface is delivered from the same path as shown in Fig 2, the role of isolation is essential in the system.

2. Identification of cause of noise problem
2.1. Driving noise of a test vehicle

A motor integral CTBA that can be installed to the rear wheels of a compact CUV vehicle was developed and equipped to a test vehicle to investigate the fuel efficiency and power performance. The basic performance fulfilled the goal, and the endurance reliability is under test.

While driving the test vehicle, a problem of inside noise exceeding the standard was identified, and the reason was assumed to be the motor integral CTBA. As a result of measuring NVH at the car, the booming noise was caused in a wide range of 50-100 Hz as shown in Fig 3, and it was the same as 1st. order vibration, which was equivalent to the number of rotation of the motor rotor. In general, if the rotation axis has the problem of 1st. order vibration, it can be improved by enhancing the unbalance of the rotating body. As the rotor installed to the motor integral CTBA satisfies the specification of G2.5 of ISO 1940, which is applied the main axis of a machine tool or turbine pumps, it can be assumed that the unbalance was not the primary cause.

Accordingly, research was conducted to analyze and solve the direct cause of 1st. order vibration of the test vehicle.

To check the problem, ODS(Operational Deformation Shape) of the motor integral CTBA installed to the test vehicle in driving mode was measured as shown in Fig 4; it was identified that up/down movement of the trailing arm bush part was excessive.

2.2. Analysis of presumed causes

Using the Electric motor diagnostic chart by W.R. Finley, Problem types with 1st. order vibration were organized. The problem types can be divided into a case where 1st. order and 2nd. order vibration is detected at the same time and a case with only 1st. order vibration. As the prototype showed only 1st. order vibration, the 7 types shown in Table 1 were analyzed. Additionally, system vibration levels of motor integral CTBA while driving and the power off were compared, and this revealed that multiple problem types could be excluded from the direct cause, as shown in the table. Vibration acceleration when driving or coasting of the test vehicle taken by the rear wheels was compared as seen in Fig 5, and a significant difference was detected in the two tests. As the case that vibration drastically reduces upon power down can be narrowed down to the two problem types of system resonance and soft foot among the listed problem causes, additional tests were performed focusing on the two types.

![Fig. 3 Noise of the test vehicle equipped with motor integral CTBA](image1)

![Fig. 4 ODS analysis on the test vehicle with motor integral CTBA](image2)

![Fig. 5 Comparison of system vibration levels while driving and the power cut](image3)

### Table 1 Electric motor diagnostic for 1st order vibration

| Problem types with increasing 1st order vibration | Vibration with power cut |
|---------------------------------------------------|--------------------------|
| Unbalance of rotor                                 | Level drops slowly        |
| Coupling unbalance                                 |                           |
| Coupling misalignment                              | Level drops slowly with speed |
| System resonance                                   | Disappears rapidly        |
| Rotor bow (Thermal Bow)                            | Some drop but high level would come with speed |
| Loose rotor parts                                  | Stator slot freq. will immediately disappear |
| Soft foot                                          | Immediately drops         |

2.3. Test for identifying the causes of system 1st. order vibration

First, FRF of the test vehicle was measured as shown in Fig 6 to check the system resonance. As a result, the system had natural Frequency of X and Y-direction at 71 Hz, but showed little direct correlation with the test vehicle having a wide range (50-100 Hz) of noise.

Second, the problem type of soft foot was investigated. Soft foot refers to shaking of a motor that is installed on soft ground or uneven base towards the direction of the mount with gaps. This is the same as diagonally wobbling chairs or tables on uneven ground, and it can be solved by aligning the same hardness of the base. As for the shape of CTBA installed on the test vehicle, it is impossible to maintain the geometry of the suspension system by installing on the same surface. Therefore, a test with a single product was performed to analyze phenomena on the relevant problem type. A dynamo test of an axle assembly unit that is a single wheel was conducted, and the beam connection part instead of the trailing arm bush was connected and fixed to the rigid test jig.

As the test results shown in Table 2, the dynamo test of the axle assembly consisting of the trailing arm and the
motor/reduction gear/wheel hub showed constantly low vibration levels even in the highest speed range.

In conclusion, as the motor with 1st. order vibration showed two phenomena that vibration Immediately drops upon power was off, and vibration decreased when it was fixed to a flat base with high hardness, soft foot was revealed to be the cause. Referring to the test results with the one fixed to the rigid test jig, it can be expected that mount tuning of the test vehicle could improve 1st. order vibration and noise.

Table 2 Comparison of motor 1st. order vibration levels

| Mount type | Test car | Dynamo test |
|------------|----------|-------------|
| Vibration (m/s² dB) | Bush | Rigid jig (Direct) |
| X | 120 | 100 | -83% |
| Y | 125 | 95 | -76% |
| Z | 120 | 100 | -83% |

2.4. Design of specifications improving trailing arm bush

1st. order vibration of the driving system decreases, if the hardness of all bush mounts is increased and strongly fixed to the car body by applying the general solution to the motor. With the method of fixing the entire motor integral CTBA strongly, however, the reaction generated to suppress vibration ends up delivering high load onto the car body mount. Although 1st. order vibration of the system is reduced, 1st. order vibration in the car body is amplified, causing vibration problem at the weak band of 50-100 Hz in the car body structure. Actually, as the test vehicle was equipped with a bush tuned twice as hard as general bushes, the vibration level was poor; accordingly, measures to solve the 1st. order vibration problem were reviewed.

Since the car body has a different structure from general motors connected to the ground with unlimited mass, new specifications were reviewed in the direction of improving the isolation performance as same as the method reviewing the engine mount. The in-wheel motor system that unsprung mass is increased due to the weight of the motor equipped onto the wheel shows higher isolation performance with bushes with lower dynamic ratio, as shown in Equation (1),(2) on transmissibility.

\[
TR \approx \frac{k_d}{k_s} < 1 \quad (1) \quad \frac{\omega}{\omega_n} > \sqrt{2} \quad (2)
\]

\(\omega\) : motor rotor frequency
\(\omega_n\) : natural frequency
\(k\) : Spring rate, kgf/mm
\(TR\) : Transmissibility
\(n\) : bush natural frequency
d: dynamic
s: static

Table 3 Specifications of the design to improve trailing arm bushes

| Shape | Existing | New |
|-------|----------|-----|
| Z direction | Static | 42 | 26.5 |
| Spring rate (kgf/mm) | @15Hz | 96 | 53 |
| | @100Hz | 192 | 106 |
| Load of mount | ++ | + |

2.5. The results of test on improvement specifications

With the developed prototype, a NVH test was conducted under the same condition as shown in Fig 7, and the inside noise and vibration levels by 1st. order vibration were identified. The noise at the driver’s seat was improved by maximum 11 dBA, and the seat vibration was enhanced by 4.9dB towards the Z direction as shown in Fig 8.

Fig. 7 NVH test for improved parts
5. Conclusion

The cause of 1st. order vibration from the motor integral CTBA was analyzed through tests, and the trailing arm bush was developed to improve vibration. They have another side effect, e.g., durability, optimization design is required based on the increased bush size when developing a new system.

The results of this research are as follows:
(1) If 1st. order vibration increases due to soft foot phenomenon, vibration of the motor integral CTBA can be improved with the even connection structure.
(2) The problem of 1st. order vibration from the motor integral CTBA can be improved, if the system isolation is enhanced.
(3) The trailing arm bush of the motor integral CTBA requires double functions of isolating the surface vibration and the driving system vibration.

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