Front-loading Quality Assurance for Noise and Vibration of Electric Powertrains

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Abstract

In recent years, the automotive industry has seen rapid progress in electrification amid the global trend toward carbon neutrality. The replacement of internal combustion engines with motors as power units has dramatically improved noise reduction in vehicles. However, this has resulted in the emergence of a new issue, in which occupants can easily detect faint sounds and vibrations that were previously masked by engine noise. This paper describes a front-loading quality-assurance approach developed to prevent noise and vibration, and achieve outstanding quietness in our first fully developed electric powertrain.

1. Introduction

In the past, our company's quality assurance in relation to noise and vibration (hereinafter referred to as "NV") from the transmissions for engine-powered vehicles was based mainly on an approach wherein the chassis and gears were first designed based on target NV values for that vehicle and the success in reaching those target NV values was checked using a single powertrain unit. For large vibration sources such as internal combustion engines, this approach is sufficient to guarantee NV quality. Thus, the main purpose of the NV evaluation using a vehicle was to conduct replication tests to identify the causes of problems only after they became apparent.

However, vehicles equipped with electric powertrains have no large noise sources such as internal combustion engines. Hence, there is a greater likelihood that occupants will notice faint NV, which have not been a problem in the past. Our electric powertrain has a structure that integrates a motor and an inverter, in addition to a gearbox. Thus, it has multiple NV sources, including the vibration of each component and resonance with the surrounding components. Conventional approaches, in which problems are individually addressed after they become apparent, require major design modifications and additional countermeasures in the final stages of development, which are risky in terms of both cost and time. Therefore, as shown in Fig. 1, we constructed and applied a front-loading quality-assurance process that proactively identifies and addresses potential problems in the early stages of development.

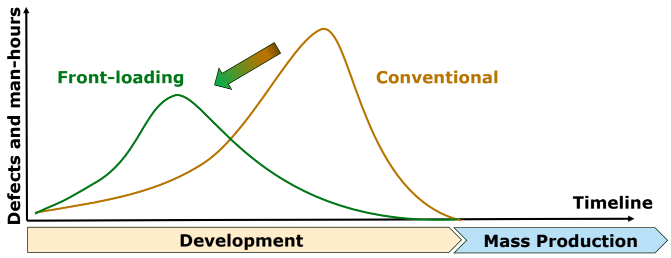

Fig. 1 Difference of conventional and front-loading

2. Development of a front-loading NV quality-assurance process

2.1 Systematic analysis of the factors that cause NV, using quality function deployment

Because NV are caused by a complex interplay between multiple factors, it is difficult to solve the root-cause of the problems by addressing each factor separately. Therefore, we used quality function deployment (QFD) to systematically organize causal relationships by translating customer-required quality into the characteristics of functional components.

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Sample of QFD results (Differs from the actual results)

Customer requirements	① NV defects	② Target	③ Allocated component characteristics	④ Sensitivity	⑤ Parameter
No noise that stand out from the background noise	Thumping noise when acceleration	$\Delta L \leq 20dB$	Shaft outer Diameter	By sensitivity line	Φ50+0.500
			Press-fit start shape	By sensitivity line	In drawing
			Bearing play	By sensitivity line	–

Fig. 2 Sample of the results by QFD

Specifically, a team led by the development department used the following procedure to organize the causal relationships.

[1] Break down a customer-requirement quality ("no unpleasant noise and vibration") into potential NV occurrences.

[2] Set target values for each NV occurrence.

[3] Extract the quality characteristics of the functional components that affect the occurrence of NV.

[4] Evaluate the degree of correlation between the customer-required quality and quality characteristics using quality tables.

[5] Translate quality characteristics into specific values for control characteristics.

The control values were extracted from a desk study, as shown in Fig. 2. To verify these values using a vehicle, we performed the physical verification described below.

2.2 Physical verification needed at an early stage

Vehicles equipped with electric powertrains have no large noise sources such as internal combustion engines. Thus, there is an increased likelihood that even faint NV will be perceived by the occupants. In addition, NV are not caused by the electric powertrain alone but by the combined effects of multiple factors, such as the transmission path to the vehicle body, resonance of surrounding components, and acoustic characteristics of the cabin. Hence, it is extremely difficult to accurately predict the level of occupant perception based on desk studies. To guarantee the high quality desired for customers, physical verification of the final product (i.e., a vehicle) is necessary from the early stages of development. Therefore, in addition to verifying the problems identified by QFD, we decided to conduct large-scale physical verifications using prototype vehicles as the core of our quality-assurance process, with the aim of discovering difficult-to-predict NV occurrences. An actual physical verification scenario is shown in Fig. 3.

Fig. 3 Physical verification

List the conditions → **Combine conditions for efficiency**

E.g.,)Condition	E.g.,) Driving pattern
Speed	Maintain 60km/h
Torque	Maintain +80Nm
Temperature	Drive with 35℃ over
Throttle vol.	Keep 25%
Gradient	Brake at 10% slope
Acceleration	Slow acceleration
Deceleration	Deceleration with e-Pedal
Steering	Full steering
Shift	Shift D to N while driving
Special	Repeat acceleration and deceleration with extremely low torque

- **-40Nm deceleration after maintaining 60km/h** (Speed + Torque)
- **Full throttle with 35℃ over** (Temperature + Throttle vol.)
- **Step on the accelerator quickly with 10% gradient** (Gradient + Acceleration)

Fig. 4 Part of the driving pattern

2.3 Design of driving patterns to detect all NV occurrences

To detect all of the potential problems, it was necessary to design a driving pattern that covered all of the possible ways in which customers drive. We designed a driving pattern that could be used to evaluate potential NV problems specific to electric vehicles, by drawing assumptions about the NV occurrence mechanisms from the QFD results. Specifically, as shown in Fig. 4, in addition to the conventional basic driving patterns, we included acceleration controls such as sudden starts and rapid acceleration, frequent changes in the regenerative braking strength, and fine torque fluctuations to detect motor noise and gear backlash noise. In addition, we included various driving conditions expected in real situations, such as driving in urban areas, on highways, in traffic congestion, and on mountain roads. Thus, we could evaluate NV occurrences that are difficult to detect under a single condition.

Furthermore, recognizing the importance of the constraints related to time and the number of prototypes, we included multiple conditions in a single driving pattern, thereby developing a holistic driving pattern that could detect all of the NV occurrences while minimizing the driving distance and time, even with limited evaluation resources.

3. Results of applying the front-loading approach

By applying the front-loading quality-assurance system, dozens of NV problems were identified that could not be predicted in the desk study. All these issues were confirmed and addressed in the early stages of development. Consequently, no rework was necessary in the final stages of development.

Fig. 5 shows examples of NV occurrences analyzed at four levels: passenger perception (1), vehicle vibration (2), powertrain vibration (3), and component characteristic values (4), which were visualized as a series of cause-and-effect structures. Each quadrant is explained as follows.

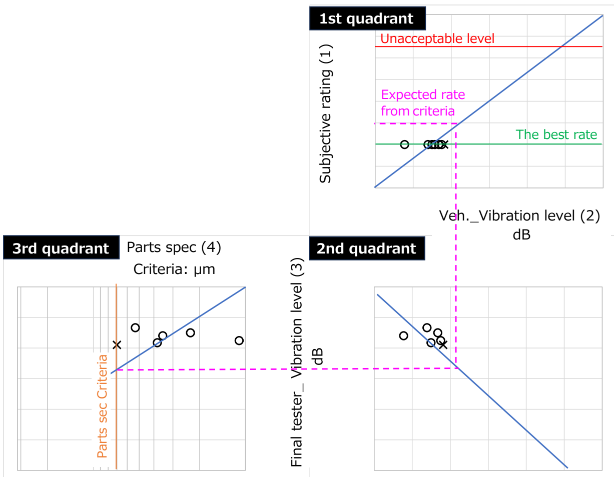

Fig. 5 Analysis results of acquired data

The first quadrant shows the relationship between the sensory score for the occupant perception (1) and vibration value measured in the vehicle (2). The occupant perception was quantified as a score. In this quadrant, no NV occurrences were perceived by the occupants, and all NV occurrences received the highest score. Therefore, there was no correlation between the occupant perception level and vehicle vibration.

The second quadrant shows the relationship between the vibration values measured on the vehicle (2) and the vibration values measured at the F/T (final tester: on-board NV assurance facility used during the manufacturing process) (3). A positive correlation was observed between vehicle vibration and F/T vibration values. This indicates that the vibration values measured on the vehicle reflect the F/T results, that is, the vibration behavior of the electric powertrain itself.

The third quadrant shows the relationship between the vibration values measured by the F/T (3) and the characteristic values of the components obtained by QFD (4). No correlation was observed between the F/T vibration and component characteristic values. This was because the vibration level was suppressed to a certain low level by the control of the characteristic values of components and thus it was masked by the surrounding vibration.

The above results indicate that the vibration level caused by the electric powertrain was relatively small compared to the overall vibration level of the vehicle and was masked by other vibrations in the in-vehicle environment. Thus, no NV occurrence was perceived by the occupants, as indicated in the first quadrant.

The occupant perception level was estimated based on the sensitivity line established from the characteristic values of the components. As indicated by the dashed line, even when an electric powertrain with the upper tolerance limit of the components was used, the NV level was lower than the occupant perception threshold. The data measured when using the worst specifications for the powertrain, which was a product that used components with the upper tolerance limits, are shown as X in Fig. 5. The results physically verified that the powertrain did not reach the occupant perception threshold, even when using the powertrain with the upper-limit specifications.

4. Discussion

By organizing the characteristic values of the components, powertrain vibration, vehicle vibration, and occupant perception level as a streamlined causal structure, we established a process for estimating the occupant perception level from component specifications. It is believed that this process enabled the verification of the validity of the target NV values at the design stage.

In addition, by conducting front-loading quality assurance based on physical verification in the vehicle, it has become possible to identify NV problems in the early stages of development and implement early countermeasures, significantly reducing the risk of design changes in the final stages of development. This approach was demonstrated to be effective for products with a wide range of NV sources, such as electric powertrains.

5. Conclusion

This approach enabled us to identify and address potential quality issues thoroughly during the development phase, resulting in the development of a full-scale electric powertrain with zero NV defects.

This method is sufficiently versatile to systematically evaluate the cause-and-effect relationships among factors that include the components, powertrain, vehicle, and occupant perceptions, and is also effective in the horizontal deployment of other products.

6. Summary

In the future, we will improve the NV-occurrence prediction accuracy by conducting further detailed analyses and compiling a database consisting of the large amount of vehicle evaluation data accumulated through this activity. We will also establish an analysis method that shortens the time needed for highly accurate NV quality assurance, thereby contributing to shorter developmental lead-times, lower costs, and higher quality.

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