Strategy for Transfer Elemental Designing and Employing Physical Characteristic Modeling of Steering Maneuvering (the Second Report)

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Our previous report introduced a theoretical method for improving steering maneuverability. The characteristics of components related to "steering feeling" were examined by this method. To determine the quantitative advantages of this theoretical method, steering and vehicle components related to steering maneuvering are evaluated. The transfer efficiency of steering system mechanical components such as the rack and pinion steering gear is minimized to achieve the target characteristics provided with this method. This paper describes the evaluation results of a mule equipped with improved steering and vehicle system components.

Key Words*: steering system, suspension system, drivability/ steering feeling, steering gear, roll steering*

1. Introduction

The steering system is important for steering feeling related to reaction force and is an important apparatus having an influence on steering feeling. One of the reason is that vehicle maneuverability is influenced by the response to steering input from the driver. Various approaches have been tried in efforts to improve steering feeling. For example, a method of designing the yaw rate gain characteristics to the steering angle depending on assist characteristics has been proposed[1]. However, a method to improve steering feeling in association with component characteristics should be improved.

In the first report[2], a model (detailed model) strictly reflecting physical characteristics was introduced in order to investigate characteristics of related components. Using this model, a method of quantitatively allocating the target design characteristics for each component was shown.

In this report, the above method was used to identify factors having influence on steering feeling from among steering-related factors and vehicle-related factors and then determine the target physical characteristics of each factor. The effect for improving the steering feeling was also quantitatively evaluated. The results are shown as follows.

2. Background

Conventionally, in order to reduce steering force, a hydraulic power steering system has been introduced. In recent years, an electric power steering (EPS) system has been introduced. EPS uses an electric motor on demand instead of hydraulic pump to reduce the energy consumption. However, EPS has issues such as fluctuation of the steering force. And transmission characteristics of EPS should be improved.

These issues are remarkable in the case of the column assist-type EPS (C-EPS®)[3]. C-EPS®, shown in **Fig. 1**, has the steering which column includes a motor and a reduction gear for assisting device. EPS also has a steering wheel, an intermediate shaft, and a steering gear, etc. This report describes the improvement of the steering feeling in this C-EPS® as an example.

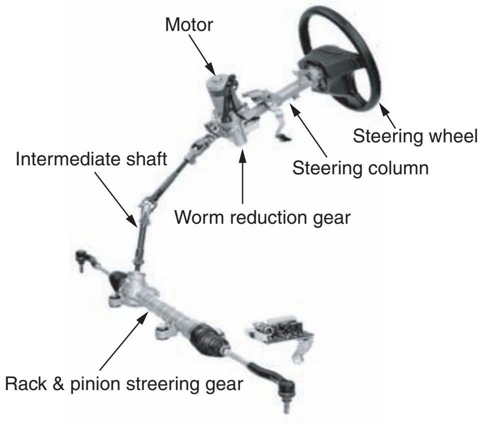


Fig. 1 Column assist type electric power steering system

3. Design of Steering-Related Elements

3. 1 Test Vehicle

Table 1 shows the steering and suspension specifications used for this investigation.

Table 1 Specifications of test vehicle steering and suspension

Module	Type
Steering	Rack & pinion steering gear assisted by electric motor on the column.
Suspension	Front : MacPherson type strut Rear : Torsion beam

3. 2 Evaluation of Test Vehicle Steering Feeling

The subjective rating result (evaluation comments) regarding the test vehicle is shown below.

①A neutral position is difficult to find during straight running.

②When steering turning is started, yaw motion starts despite the fact that roll does not appear as expected.

③Yaw motion does not appear smoothly in accordance with steering the steering wheel, which causes difficulty in changing the direction of the vehicle.

Among these evaluation comments, comment ③, in which contribution of both of the steering and the vehicle is clear, will be addressed.

An actual vehicle subjective rating was carried out by an expert vehicle evaluator fully experienced in evaluating, supervising and instructing in the area of automaker and chassis component maker product evaluations. The evaluation conditions were a vehicle speed of 60 to 100 km/h, steering angle of 0 to 90 degrees, and an asphalt road surface (friction coefficient μ:0.75).

3. 3 Setting of Improvement Targets

In order to calculate improvement target values, yaw rate characteristics in response to steering torque (**Fig. 2**) were investigated based on measurement results from actual vehicle maneuvering. The solid line shows actual measurement data, and the chain line shows the approximate curve thereof.

Until a steering torque of about 2 N･m is reached, no significant yaw rate appears. Steering torque of 2 N･m or more, on the other hand, causes rapid increase of the yaw rate increase gradient. Steering torque of about 2.8 N･m causes reduction of the yaw rate increase gradient. This characteristic supports the above evaluation comment ③ of "yaw motion does not appear smoothly." Therefore, the characteristic shown by the broken line in **Fig. 2** is set as a target. Specifically, when steering torque reaches about 1.2 N･m, the yaw rate is increased with the gradient of 2.8 N･m or more, and the gradient change is reduced.

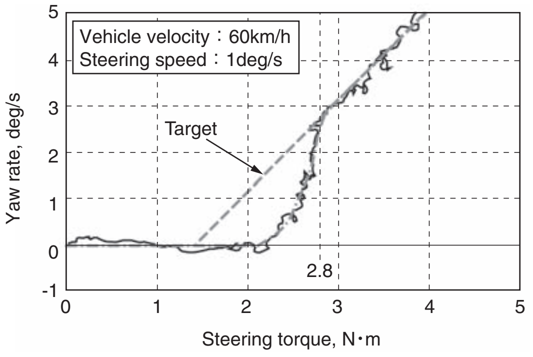


Fig. 2 Relationship of steering torque and yaw rate

3. 4 Investigation of Improved Element

The detailed model in the first report was used to investigate parameters able to achieve the target characteristics. As a result, the target characteristics were considered to be achieved by friction reduction of the elements shown in the following (a) to (c). A design method for reducing these friction factors is described below.

(a) Friction of rack & pinion gear
(b) Friction of reduction gear
(c) Motor resistance (hysteresis loss)

3. 5 Friction of Rack & Pinion Gear

3. 5. 1 Features of Rack & Pinion Gear Mechanism for Steering

A gear mechanism generally has a backlash between the teeth surfaces engaged with each other. This is for the purpose of preventing the smooth engagement of gears from being disturbed by uncertain factors such as eccentricity, manufacture error, thermal expansion, and assembly error of gears. However, the steering rack & pinion gear mechanism (**Fig. 3**(a)) must transmit both left and right rotation angles from steering input to the tires accurately and with quick response. In order to avoid rattle noise caused by impact from the tire, the rack is pushed by a support yoke to the pinion as shown in **Fig. 3**(b). This consequently always maintains backlash at zero at the part where the rack is engaged with the pinion. Rack & pinion gear mechanism for steering has such a special feature comparing to an ordinary gear mechanism.

3. 5. 2 Engagement Area Issues

In the above structure, the gear engagement part is structured so that both tooth surfaces are engaged with each other (one gear's tooth front and back surfaces both contact the other gear's tooth surfaces at the same time). In this case, the rack tooth is being meshed with the pinion tooth groove in wedge-like manner. The geometric shape of the gears and their assembly cannot be perfect, and the apparatus also is subject to elastic deformation due to load and thermal deformation. Therefore, generally one tooth surface has involute contact and a tooth tip of the back tooth surface has some trochoid interference (**Fig. 4**). This phenomenon is called, in this report, "tip interference and both tooth surface engagement". The trochoid interference at the tooth tip prevents the transmission of constant velocity motion and also may cause increased friction$^{4)}$.

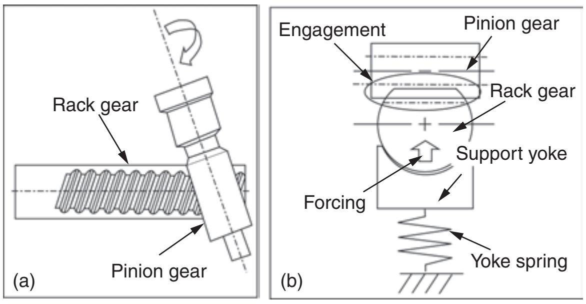


Fig. 3 Rack & pinion engagement and support parts

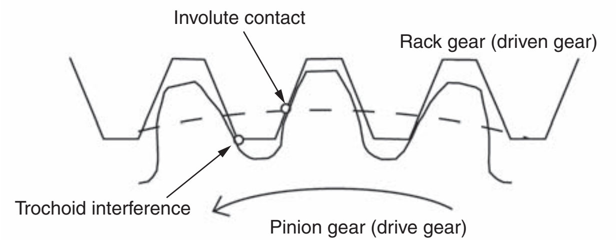


Fig. 4 Rack & pinion gear engagement

3. 5. 3 Design Objective

In order to improve transmission efficiency, a gear exclusively designed for the steering was examined in order to suppress "the tip interference and both tooth surface engagement" when the backlash was zero for improvement of transmission efficiency.

The new design is different from an original design in that it has a reduced module, increased teeth number, and increased pressure angle. This design allows the engaged teeth to have reduced length and reduced elastic deformation amount so that the engagement of both tooth surfaces is easily cancelled thereby to reduce the trochoid interference at the tooth tip. In order to reduce slip, the engagement length when the tooth surfaces are moved toward each other and that when the tooth surfaces are moved away from each other are equalized. In addition, in order to reduce the increase of tooth flank stress during engagement in C-EPS®, the increase of the tooth contact area was studied.

3. 5. 4 Detailed Examination of Tooth Contact

The phenomenon of tooth contact reaching the end of the tooth surface (uneven contact) causes eccentric wear and breakage. This uneven contact is caused by various factors that cannot be controlled by the design, such as tooth elastic deformation during operation under load or axis alignment error. In order to prevent these, in consideration of the above factors, the shape of three-dimensional tooth surfaces necessary to provide proper tooth contact to the tooth surface center under rated load was determined (**Fig. 5**).

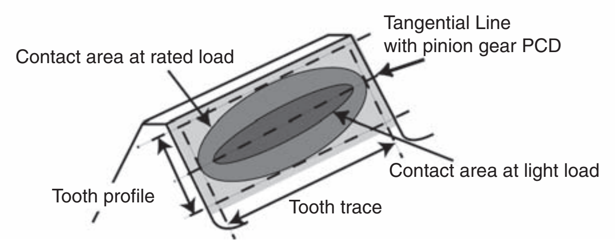


Fig. 5 Proper tooth contact (schematic diagram)

3. 5. 5 Development Cycle

In order to achieve the above tooth contact, sufficient accuracy is required, and therefore the development cycle shown in **Fig. 6** was introduced.

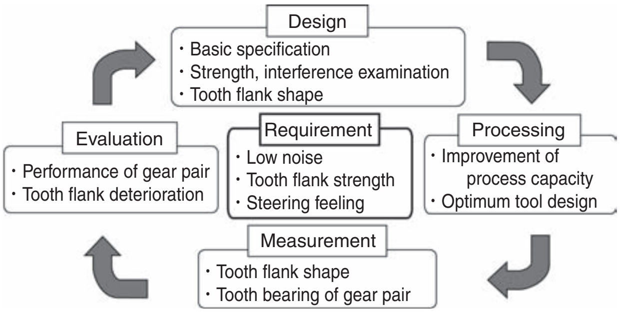


Fig. 6 Development cycle

Ⅰ. Machining technique
Vibration of the hob while attached to the machine was reduced and tooth surface shaping accuracy was improved.

Ⅱ. Measurement technique
CAD used in design was linked to the three-dimensional measurement machine so that tooth surface error, pitch error, etc. from the reference position shown in the drawing could be measured.

Ⅲ. Evaluation technique
A mesh testing machine capable of changing alignment (**Fig. 7**) was developed so as to achieve measurement of the gear pair transmission efficiency.

Ⅳ. Design technique
Design for mechanical components was reviewed and improved.

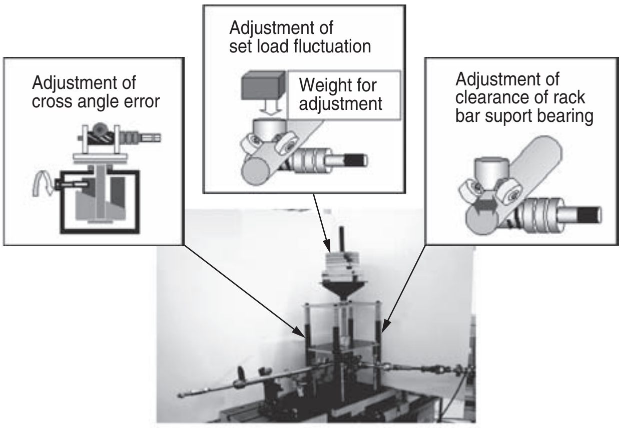


Fig. 7 Transmission error measurement instrument of gear pair

3. 5. 6 Guideline of Design for Mass Production

In order to use these techniques for mass production design, design standards and component commonization should be considered. **Figure 8** shows the guideline for actual application range of the tooth flank stress, tooth tip thickness and tooth height threshold obtained through individual optimization.

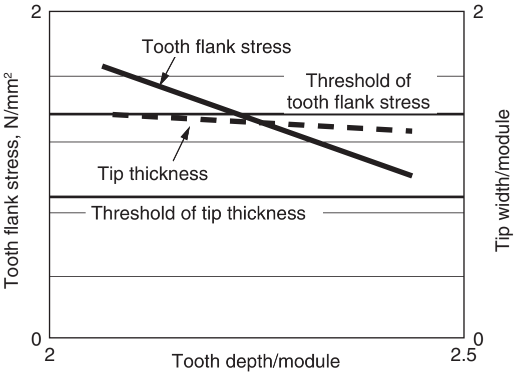


Fig. 8 Guideline of gears for mass production

3. 6 Performance Evaluation of Rack & Pinion Gear

A rack & pinion gear assembly incorporating the above design elements was evaluated. One example of the results is shown in **Fig. 9**, in which the horizontal axis shows the rack stroke and the vertical axis the pinion torque.

When compared with the original rack & pinion gear, the new-design one shows about 51%-reduced pinion rotation torque on an average (broken line) and 97%-transmission efficiency. Thus, the new-design product has achieved smooth rolling movement under the condition of unfavorable engagement of the tip interference tooth surfaces.

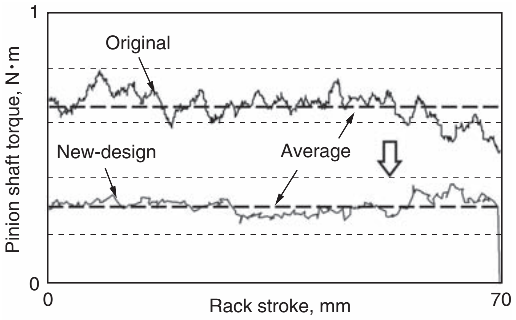


Fig. 9 Rack stroke and pinion torque characteristics

3. 7 Reduction Gear Friction

(1) Issues in EPS reduction gears

In an EPS reduction gear (worm reduction gear portion in **Fig. 1**), amplified motor torque is transmitted to the steering shaft. The worm gear has low transmission efficiency due to high friction caused by large slipping between the tooth surfaces. Furthermore, in many cases the EPS reduction gear is made of resin. That is one of the reasons for friction fluctuation related to maintaining gear accuracy.

(2) Design of reduction gear

The new-design product uses a steel helical gear for the purpose of reducing friction and confirming the effect of improving the transmission efficiency. The newly designed one has been prepared with high precision machining through designing to realize appropriate tooth contact by selecting optimal specifications the same as those in the above-described rack & pinion gear design.

As a result, the new-design product showed 24%-reduced torque on an average (broken line) under no load when compared with the original one. The new-design product also achieves 97%-transmission efficiency (**Fig. 10**).

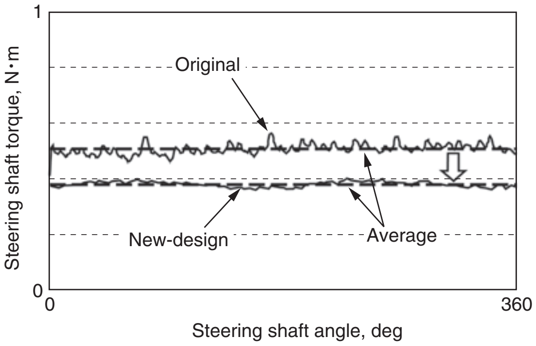


Fig. 10 Reduction gear torque characteristics under no load

3. 8 Resistance of Motor

By reducing the hysteresis loss of the magnetic steel sheet, the new-design product achieved about 29%-reduced motor torque under no load on an average (broken line) when compared with the original one (**Fig. 11**).

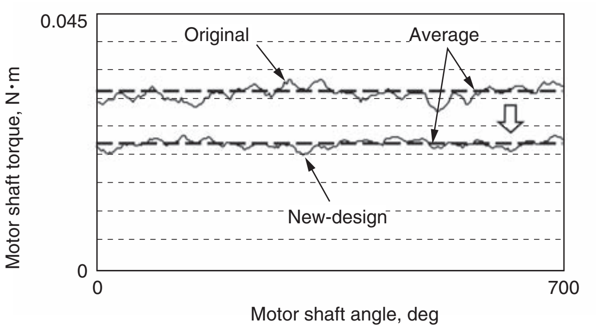


Fig. 11 Motor shaft torque characteristics under no load

3. 9 Validation of Friction Reduction Effect

The new-design product was installed in a vehicle and was subjected to the same measurement as in **Section 3.3**. **Figure 12** shows the characteristics of the yaw rate in response to steering torque.

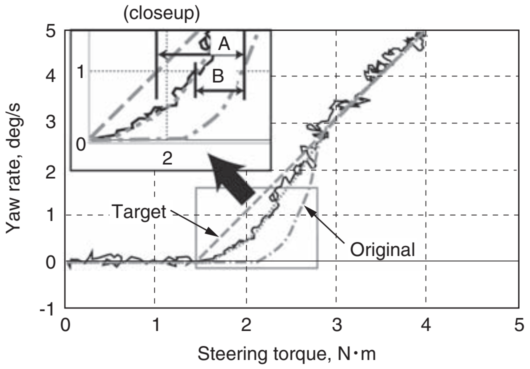


Fig. 12 Steering torque and yaw rate characteristics

When compared with the characteristics of the original product (chain line), the characteristic of the new-design product (solid line) is closer to the target characteristic (broken line). In order to evaluate the achievement degree compared with the target steering feeling simply, the following indexes are introduced (expanded diagram in **Fig. 12**). Specifically, the difference between the steering torque of the original product and the target steering torque is assumed to be A when the yaw rate is 1deg/s. Similarly, the difference between the steering torque of the original product and that of the new-design product is assumed to be B. The achievement rate is represented by the ratio of B to A (=B/A × 100). In this example, the achievement rate is 40%.

The following evaluation comment was obtained: "The yaw motion appeared smoothly but the turning of the vehicle is still difficult."

4. Improvement of Vehicle-Related Elements

4. 1 Analysis of Actual Vehicle Measurement Data

In the above-described steering-related product with the new design, while a maximum improvement in the efficiency for realizing the target characteristic was realized, the effect by the improvement was insufficient. Thus, the improvement regarding the evaluation comment ③ is studied by elements other than the steering system. Based on the measurement result in **Section 3.3**, the steering angle is shown by the horizontal axis and the yaw rate by the vertical axis in **Fig. 13**, in which the actual measurement data is shown by the solid line and the approximate curve thereof is shown by the chain line.

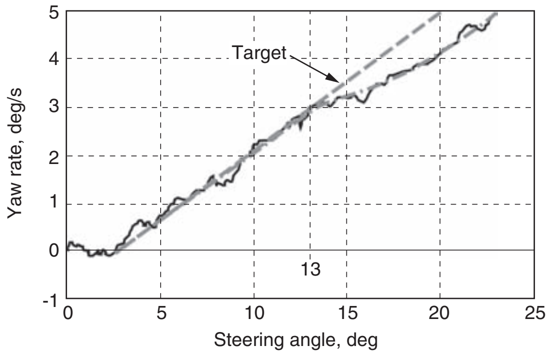


Fig. 13 Steering angle and yaw rate characteristics

In **Fig. 13**, steering angles in the range from 3 to 13 degrees correspond to an increase of the yaw rate with a fixed gradient, but the steering angle of about 13 degrees corresponds to a decrease of the increasing gradient. This characteristics support the evaluation comment ③ "the turning of the vehicle is difficult." Then, the target was set to equalize the gradient corresponding to steering angles of 13 degrees or more to the gradient corresponding to steering angles of 3 to 13 degrees.

4. 2 Study of Improvement Elements

Using a detailed model, analysis was made with the characteristics of the vehicle-related elements as parameters. As a result, it presumably was effective to reduce the variation of the toe angles of the respective front and rear tires when the suspension had a stroke operation.

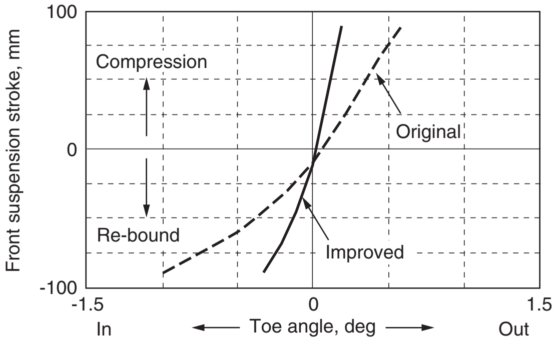


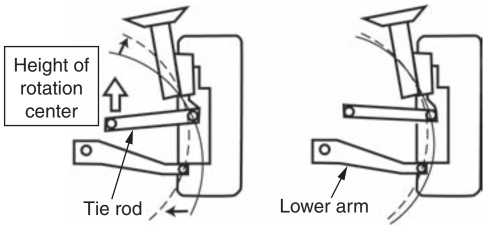
Fig. 14 Front wheel toe angle and suspension stroke characteristics

4. 3 Variation of Front Wheel Toe Angle

Figure 14 shows the characteristics of the front wheel toe angle variation when the horizontal axis shows the toe angle and the vertical axis shows the suspension stroke with the compression side being positive.

In the case of the original product (broken line), in accordance with the stroke variation in the compression direction of the suspension at the outer turning side, the outside wheel shows the variation in the toe-out direction and the inside wheel shows the variation in the toe-in direction. These toe angle variations correspond to reduced tire angle and suppress change of the vehicle direction5). This phenomenon is caused by the difference in the upper and lower swing trajectories between the steering tie rod and the suspension lower arm (**Fig. 15**(a)).

In order to reduce this swing trajectory difference, the gear box mount height was changed and the tie rod swing angle was changed to be appropriate (**Fig. 15**(b)). The result showed the reduced variation of the front wheel toe angle during the suspension stroke both for the inside wheel and the outside wheel.



(a) Original (b) Improved

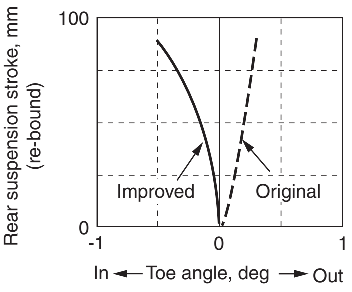
Fig. 15 Schematic diagram of front wheel toe angle variation with suspension stroke

4. 4 Variation of Rear Wheel Toe Angle

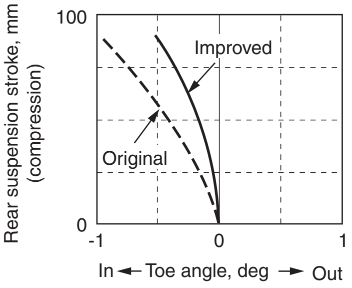
Figure 16 shows the characteristics of the rear wheel toe angle variation to the road surface when the horizontal axis shows the toe angle and the vertical axis shows the suspension stroke with the compression side being positive.

A situation is assumed in which the suspension has a stroke operation when the vehicle body rolls during turning. In **Fig. 16**, the broken line shows the characteristics of the original product for which the turned inside wheel (a) changes in the toe-out direction and the turned outside wheel (b) changes in the toe-in direction. These results show that both the rear outside wheel and rear inside wheel toe angles change to the inner side of the turning direction. Thus, the rear part of the vehicle body moves to the corner after the start of turning, thus suppressing the direction of the vehicle from being changed.

Then, the characteristics were changed so that the suspension arm was substantially horizontal at the initial position and both the turned inside wheel and turned outside wheel could have the same direction and substantially the same toe angle change amount (solid line of **Figs. 16**(a) and **16**(b)). **Figure 17** is a schematic diagram of the toe angle variation in which the result of the original product is shown in (a) and that of the improvement in (b).

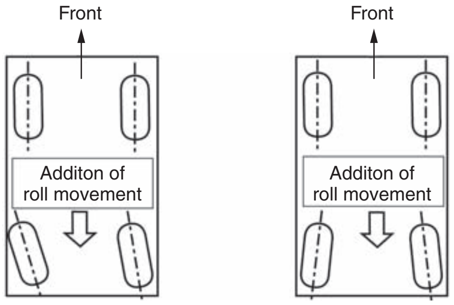


(a) Inside wheel



(b) Outside wheel

Fig. 16 Rear wheel toe angle and suspension stroke characteristics



(a) Original (b) Improved

Fig. 17 Schematic diagram of rear wheel toe angle variation with suspension stroke

4. 5 Validation by Actual Vehicle

With regard to the improved specifications, the same measurement as in **Section 3.3** was performed. **Figure 18** shows the yaw rate characteristics to the steering angle.

As in **Fig. 18**, the gradient according to the improved specifications is closer to the target gradient (broken line) than in the case of the original specifications. In order to evaluate the achievement of the improvement in the steering feeling simply, the same indexes as those in **Section 3.9** are introduced (expanded diagram in **Fig. 18**). In this validation, the achievement was evaluated with regard to the steering angle when the yaw rate was 4 deg/s. The result shows about 70%-achievement of the target value.

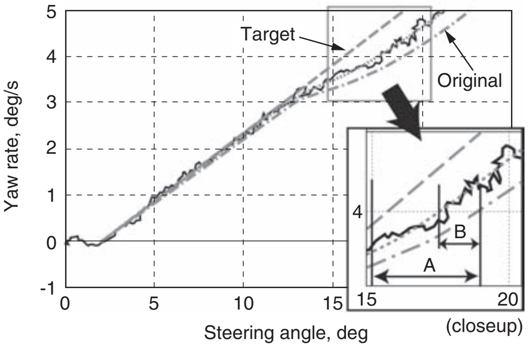


Fig. 18 Steering angle and yaw rate characteristics

5. Summary of Factors Influencing Steering Feeling

In the previous sections, steering-related elements and vehicle-related steering elements have been improved with regard to evaluation comment ③. As a result, with regard to the smoothness of the yaw appearance as an example, significant effect was obtained with regard to the steering-related improvement. With regard to the variability of the vehicle direction, significant effect was obtained by improvement of the vehicle-related elements.

In order to allocate the target system performances to element characteristics, it is necessary to associate the respective target performance and evaluate the performance in more detail. Thus, a detailed model was used to find improved elements having an influence on steering feeling (**Table 2**).

The effects of the respective improved elements were evaluated by an actual machine to calculate the ratio of influence on steering feeling. The influence ratio is the ratio obtained by dividing the achievement by respective element based on the indexes described in **Section 3.9** by the sum of the achievements obtained by all elements. **Figure 19** shows an example when the evaluation comment ③ is used as an index.

As seen in **Fig. 19**, the influenced items and the influence ratios thereof are different depending on the details of the evaluation.

Similar improvement was also performed regarding the evaluation comments ① and ② in **Section 3.2**. In this report, only the correlation between the evaluation comments and the improved elements is shown in **Fig. 20** because space is limited.

As shown in **Fig. 20**, one evaluation comment is influenced by many elements. On the contrary, one improved element sometimes has an influence on a plurality of evaluation comments. Thus, it can be easily understood that element improvement by focusing on one evaluation comment may have an adverse influence on other evaluation contents.

Table 2 Improved elements

Elements	Purpose for improvement
Steering mount stiffness ・Column housing ・Rack gear box	In early stages of steer, the rack stroke become stable.
Steering components stiffness ・Torsion bar ・Intermediate shaft	In early stages of steer, the rack stroke become accurate, and the tire angle is stable in case of disturbance.
Steering over-all ratio	Ratio variation between steering and tires is reduced.
Front tire Alignment ・camber ・caster ・toe	In early stages of steer, the abrupt vehicle response toward lateral direction is suppressed, and the roll and yaw movement becomes smooth.
Roll center	In early stages of steer, the roll and yaw movement is controlled easily.
Shock absorber dumping characteristics	In early stages of steer, the roll and yaw movement is controlled easily.
Lower arm mount stiffness	The tire angle variation occurred by lateral force is reduced.
Front strut mount stiffness	In early stages of steer, the suspension movement become smooth, and the roll is made smoothly to generate, so that the yaw rate is generated according to the roll.
Body stiffness around front suspension	
Rear tire initial toe angle	In early stages of steer, the decrease of yaw rate by rear tire is suppressed.

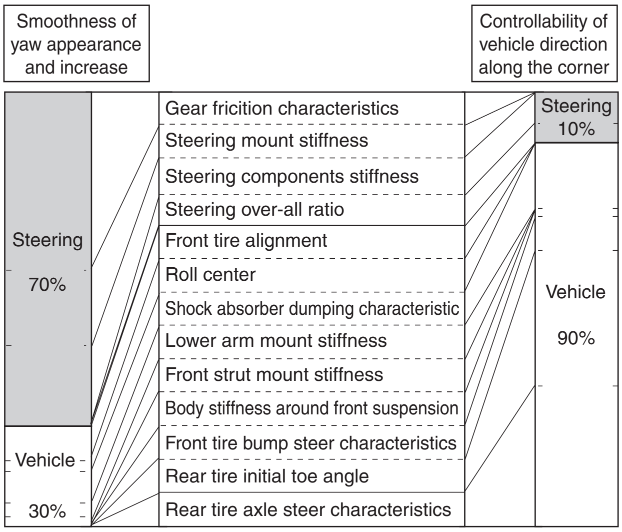


Fig. 19 Contribution ratio to evaluation comment ③

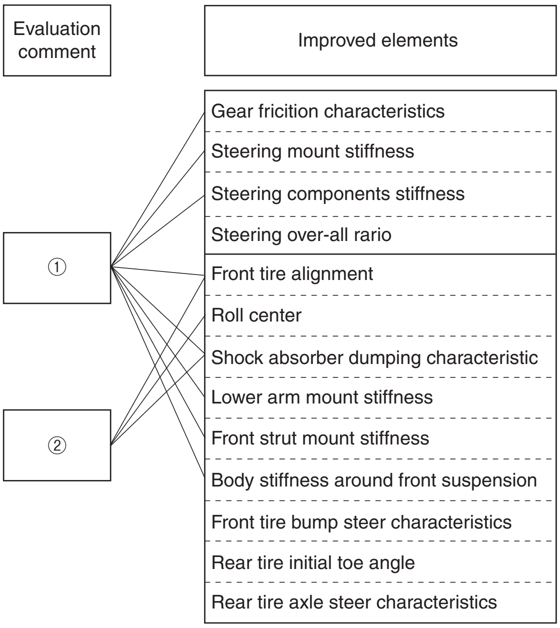


Fig. 20 Correlation between evaluation comments and improved elements

6. Issues in Realization of Target Steering Feeling

If a single element is optimized by focusing on the steering feeling performance only, other performance features may not be achieved such as system quietness and robustness. Furthermore, in order to achieve proper steering feeling performance in mass production, a design guideline is required that takes into consideration such limitations as component commonization.

For example, a discussion cannot be avoided regarding the suitability for the design standards (**Fig. 8**) described in **Section 3.5.6** (mass production gear design).

In consideration of the above, in order to achieve the target steering feeling, such a design is required that considers the influence of respective components on the system. In reality, there are many cases in which optimization is achieved by the better countermeasures considering the balance of the merits and the demerits.

7. Summary

- The method suggested in the first report was used to identify the factors influencing steering feeling from among steering-related components and vehicle-related ones. Then, the target physical characteristics of these influencing factors were determined.
- In order to improve steering feeling for which the steering-related components are mainly responsible, effective measures were found to be reduction of gear mechanism friction and reduction of motor rotation resistance, etc. With regard to the rack & pinion gear in particular, a gear design method was shown that could achieve a small module without deteriorating strength.
- A method for quantitatively showing the influence ratio between the steering-related components and vehicle-related ones contributing to the steering feeling was described.

8. Conclusion

Because of such limitations as design standards and component commonization, the optimization of components alone is insufficient to achieve the target system performance. The next report will describe, as a means for realizing an optimized vehicle system, an ideal transmission characteristic that achieves the target steering feeling by using a steer-by-wire (SBW) system for which the transmission characteristic can be set freely.

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