

Strategy for Transfer Elemental Designing, Employing Physical Characteristic Modeling of Steering Maneuvering (First Report)^{*1}

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Improvement of value-added steering maneuvering is required more than ever and for a wider range of passenger vehicles. Steering is one of the key systems to achieve better vehicle maneuvering. Sensory evaluation of "steering feeling" can hold contingency designing strategy. But, uncertainty of human factors should be taken into account for evaluation of physical quantities. Some methods that specify the relation between "steering feeling" and performance of vehicle dynamics have been proposed but not practically used for actual design of steering components. This paper describes a theoretical method with a detailed steering model that specifies quantitative performance and physical quantities for components.

Key Words: steering system, drivability, design/ steering maneuvering, steering feeling, sensory evaluation

1. Introduction

Automotive performance has improved remarkably with the progress of technology. However, not only reduced failure rates and age deterioration of each part but also the improvement of added-value features such as ease of practical use continue to be demanded.

The steering system is an important component, and such operational features as reaction force change in response to steering input from the driver and response during vehicle turning are important to improving vehicle maneuvering¹⁾. It is difficult to quantitatively evaluate vehicle steering performance, just as vehicle maneuvering, because sensory perceptions are involved. Because of this, many attempts have been made in various fields to quantify operability and use this in designing. For example, in the field of master-slave type remote-control systems, quantitative evaluation of operability and guidance regarding control design have been provided²⁾. However, in regard to vehicle sensory evaluations, there are no examples quantitatively clarifying the relation with element part characteristics with such evaluations.

In that regard, we introduced a steering system model that strictly reflects physical characteristics concerning steering performance and analyzed steering system transmission characteristics utilizing this model. This

paper describes a technique for deciding physical values related to transmission characteristics as design target values for each part.

2. Steering System Performance

Table 1 shows examples of steering system performance requirements. In order to pursue improvement of these performance characteristics theoretically, quantitative target values must be set in the system design phase. Further, it is necessary to clarify the targeted performance values of each element part as physical values.

The functions of steering and assist torque (**Table 1-i**) are evaluated by the power steering assist amount and other characteristics over time. Regarding strength and durability performance (**Table 1-ii**), the steering system is required to maintain basic functions even under vibration, impact and other loads. Because these can be evaluated by clear numerical criteria, such performance characteristics have been efficiently improved in actual development.

Regarding steering feeling (**Table 1-iii**), on the other hand, improvement of performance has depended on sensory evaluations carried out by skilled evaluators coupled with tuning evaluations.

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Table 1 Steering system performance requirements

Requirement	Performance
(i) Function of steering and assist torque	• Steering effort • Power-assist • Force deflection • Free play of steering wheel • Noise • Vibration etc.
(ii) Strength, durability	• Steering wheel torque • Force on the road wheels • Vibrational input etc.
(iii) Steering feeling	• Smoothness of torque • Feeling of inertia, viscosity, friction etc.

3. Issues in Efforts to Improve Steering Feeling

3.1 Sensory Evaluation

Steering feeling is an index used to sensorially evaluate the relationship between changes in steering effort required during steering operation and vehicle behavior. **Table 2** shows examples of terms used in such evaluations. **Table 3** shows the example of steering feeling evaluations applying the pilot rating technique³⁾.

Table 3 indicates that the index of vehicle C's inertia feeling is low. However, it does not quantitatively answer such questions as, "Which components should be improved?" or "How much should the value be improved?" and these sensory ratings cannot be used theoretically in design work.

Table 2 Expressions for steering feeling

Phenomena and function	Sensory evaluation term
S. A. T. (self aligning torque) transformation to steering wheel	• On-center feel • Build-up feel • Direct feel etc.
No sticky or dragged feeling	• Smooth without stick • Low-friction etc.
Moderate effort during quick steering	• Low-inertia feel • High rigidity feel • Wall effect etc.
Stable on-center or at keeping angle	• Stability • Steadiness • Solid feel etc.
S. A. T. transformation without variation or vibration	• Smoothness • Continuous • Silky etc.
Assist torque characteristics	• Easy driving • Preferred/not preferred etc.

Table 3 Example of pilot rating of steering system

Evaluation items	Vehicle A	Vehicle B	Vehicle C
Returnability	6	5.5	6
Low-friction feel	6	6	5.5
Low-inertia feel	6	6	4
On-center feel	6	6	5.5
Response	6	6	6

3.2 Quantitative Sensory Evaluation

One problem is the fact that feedback from evaluations carried out by the skilled evaluators mentioned in the previous section does not constitute quantified physical values. Moreover, sensory evaluations depend on the evaluator's skill, and the fact that evaluations may differ between evaluators depending on their sensorial perceptions must be taken into account. Therefore, it has been proposed that the correlation between sensory evaluation results and physical values representing vehicle characteristics be investigated by the multivariate analysis technique^{4), 5)}. The example of analyzing "steering wheel torque response feeling" is shown as follows:

<Steering wheel torque response feeling>

Regarding test conditions, slalom driving at vehicle speeds of 20-140 km/h and maximum lateral acceleration of 1.96-2.94 m/s² was performed. The response feeling was judged as good when the steering wheel torque value at around 0 deg steering wheel angle was within the range of 0.1-0.2 Nm (**Fig. 1-①**)⁵⁾.

Guidelines regarding vehicle characteristic targets to achieve the targeted steering feeling using such an evaluation approach have been issued. Moreover, it is possible to clarify target characteristic indexes for steering systems by the basic technique of transmission system modeling⁶⁾. However, to achieve the targeted steering characteristics, accurate modeling is required for quantification of detail specifications for each component.

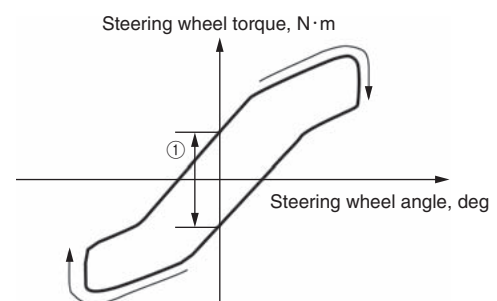


Fig. 1 Example of steering torque and steering angle characteristics

4. Analysis of Transfer Characteristics and Performance of Steering System

4.1 Investigation of Steering System Target Performance

Figure 2 shows the feedback control loop of the steering system including the driver. For example, the driver decides the steering angle based on traffic situations and inputs this to the steering wheel system. This input is transmitted to the chassis system and tires, and the reaction force from the road causes the movement of the vehicle. In this case, chassis means vehicle components such as the suspension that influence steering characteristics. At this time, the force generated in the tires is transmitted through the steering system, and it balances the steering force. The driver recognizes the vehicle movement by sight, somatic sensations, deep sensorial perception, etc. and controls the vehicle accordingly by feedback control. The steering system including the driver builds the feedback loop.

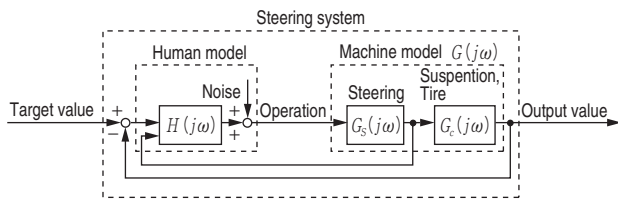


Fig. 2 Driver - vehicle model

It is known that each driver has his own transmission characteristics (driver model: $H(j\omega)$) and these characteristics are adjusted to adopt to the controlled system or turbulence (adjustment operation). Therefore, it is important that transfer function $G(j\omega)$ of the entire vehicle system be estimated to reduce driver work load. It is similar to other controlled systems in that it is preferable that the open loop gain of the system be near -20 dB/dec in the area of a crossing over frequency to achieve excellent response, attenuation, and steady-state characteristics in this control system loop. Additionally, it is better from the viewpoint of easy operation that this gain be high enough in the low frequency zone and low enough in the high frequency zone⁷⁾⁻⁹⁾.

The target characteristics of the machine model ($G(j\omega) = G_s(j\omega) \cdot G_c(j\omega)$) are not provided in a single assumption considering the difference and deviation of $H(j\omega)$. To estimate the target characteristics of $G(j\omega)$ by numerical analysis, typical driver characteristics are applied.

In the vehicle design phase, the target characteristic of the output yaw rate γ to input torque T_h is defined as in equation (1). At this time, if chassis characteristic $G_c(j\omega)$ is decided, target characteristic $G_s(j\omega)$ of the steering wheel can be quantitatively estimated as shown in equation (2).

$$\gamma(j\omega) = G(j\omega) \cdot T_h(j\omega) \quad (1)$$

$$G_s(j\omega) = \frac{G(j\omega)}{G_c(j\omega)} \quad (2)$$

4.2 Strict Model of Steering System

To design steering feeling using the target characteristic $G_s(j\omega)$ obtained in Section 4.1, the correlation with characteristics of $G_s(j\omega)$ and of each element part in the steering system should be estimated. Therefore, modeling that expresses physical characteristics of the steering system as strictly as possible is needed. Figure 3 shows an example model of a column shaft assistance type power steering system (C-EPS[®]). Item numbers ① through ⑨ in Fig. 3 are component blocks composing the steering system.

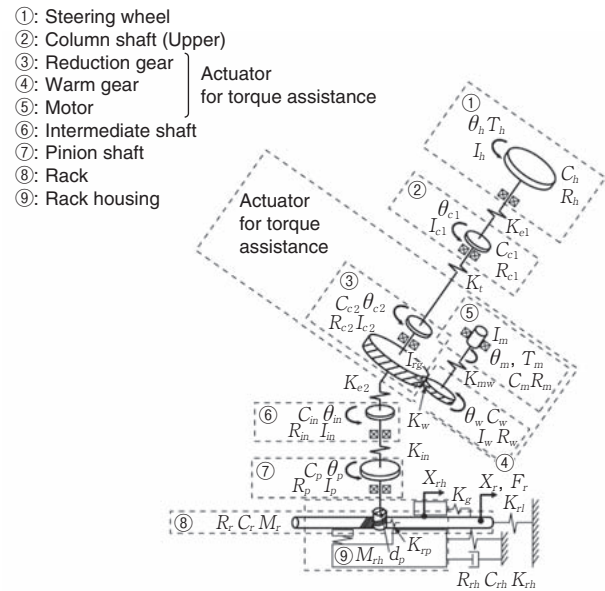


Fig. 3 Steering model (C-EPS[®])

I and M indicate inertia, K is elasticity, R is friction, and C is viscosity. T is torque, θ is displacement angle, F is force, and X is displacement. Moreover, subscript h means an steering wheel part, e_1 means an energy-absorbing mechanism, c_1 means an upper column part, t means the torsion bar, c_2 means lower column parts including the reduction gear, w means the worm gear, m means the motor, e_2 means a lower energy-absorbing mechanism, in means the intermediate shaft, p means the pinion shaft, r means the rack, rh means the rack housing, g means the rack boots, and rl means the rack load part. K_{c2w} is elasticity in the reduction gear, K_{rp} is elasticity between the pinion and rack gear, d_p is pitch diameter of the pinion gear, and K_{mw} is elasticity of the interface part between the worm gear and motor axis.

Characteristics of component not specified in **Fig. 3** are defined as follows. The influence of fixing parts of the column housing is considered by R_{ci} , C_{ci} ($i = 1, 2$). The torque change according to phases of the intermediate shaft universal joints is considered by R_{in} and C_{in} . Electromagnetism and mechanical torque fluctuation of the motor is taken into account as parts of R_m and C_m . R_r and C_r are friction between the rack bar and rack housing, and the influence of the yoke sheet pressure on the rack and friction of the bush are considered. Elasticity K_{rl} corresponds to the reaction force of the rack from the tires corresponding to rack stroke X_r .

This model is described by equations (3)-(11) at blocks of each component (①-⑨) shown in **Fig. 3**. Equations (3)-(9) are equations of motion along the direction of the rotation axis. Equations (10) and (11) are equations of motion along with stroke direction of the rack. K , R , and C are functions related to displacement and speed of each part, including nonlinearity. These characteristics are indicated by $\alpha_{Ai}(\theta_j)$, $\beta_{Ai}(\theta_j)$ ($A = K, R, C$ $i, j = h, c_1, \dots$).

$$I_h \ddot{\theta}_h = T_h - \alpha_{Ch}(\dot{\theta}_h) - \alpha_{Rh}(\theta_h) - \alpha_{Kel}(\theta_{c1}, \theta_h) \quad (3)$$

$$I_{c1} \ddot{\theta}_{c1} = -\alpha_{Cc1}(\dot{\theta}_{c1}) - \alpha_{Rc1}(\theta_{c1}) - \alpha_{Kt}(\theta_{c1}, \theta_{c2}) - \alpha_{Kel}(\theta_{c1}, \theta_h) \quad (4)$$

$$(I_{c2} + I_{rg}) \ddot{\theta}_{c2} = -\alpha_{Cc2}(\dot{\theta}_{c2}) - \alpha_{Rc2}(\theta_{c2}) - \alpha_{Ke2}(\theta_{c2}, \theta_{in}) - \alpha_{Kw}(\theta_{c2}, \theta_w) + \alpha_{Kt}(\theta_{c1}, \theta_{c2}) \quad (5)$$

$$I_w \ddot{\theta}_w = -\alpha_{Cw}(\dot{\theta}_w) - \alpha_{Rw}(\theta_w) - \alpha_{Kmw}(\theta_w, \theta_m) + \alpha_{Kw}(\theta_{c2}, \theta_w) \quad (6)$$

$$I_m \ddot{\theta}_m = T_m - \alpha_{Cm}(\dot{\theta}_m) - \alpha_{Rm}(\theta_m) + \alpha_{Kmw}(\theta_w, \theta_m) \quad (7)$$

$$I_{in} \ddot{\theta}_{in} = -\alpha_{Cin}(\dot{\theta}_{in}) - \alpha_{Rin}(\theta_{in}) - \alpha_{Kin}(\theta_{in}, \theta_p) + \alpha_{Ke2}(\theta_{c2}, \theta_{in}) \quad (8)$$

$$I_p \ddot{\theta}_p = -\alpha_{Cp}(\dot{\theta}_p) - \alpha_{Rp}(\theta_p) - \alpha_{Krp}(\theta_p, X_r, d_p) + \alpha_{Kin}(\theta_{in}, \theta_p) \quad (9)$$

$$M_r \ddot{X}_r = -\beta_{Cr}(\dot{X}_r, \dot{X}_{rh}) - \beta_{Rr}(X_r, X_{rh}) - \beta_{Rrs}(X_r, X_{rh}) - \beta_{Ks}(X_r, X_{rh}) - \beta_{Kd}(X_r) + \beta_{Krp}(\theta_p, X_r, d_p) \quad (10)$$

$$M_{rh} \ddot{X}_{rh} = -\beta_{Crh}(\dot{X}_{rh}, \dot{X}_r) + \beta_{Rr}(X_{rh}, X_r) - \beta_{Rrh}(X_{rh}) - \beta_{Krh}(X_{rh}) + \beta_{Ks}(X_r, X_{rh}) \quad (11)$$

Figure 4 shows the calculation and measurement comparison of the frequency response characteristic of rack axis power F_r to steering wheel torque T_h . This result shows that this model enables performance to be analyzed simulating the actual steering system.

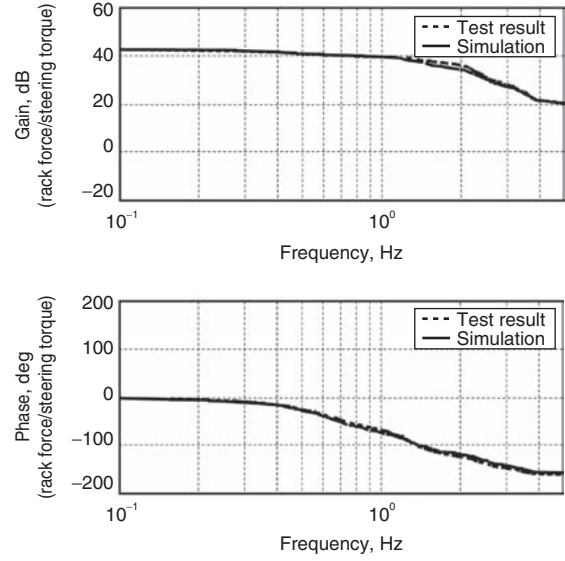


Fig. 4 Bode diagram comparison

4. 3 Estimation of Performance Targets for Component Parts

Transfer function G_a , which equations (3)-(11) approximate with linear characteristics, is described by equation (12).

$$G_a(s) = \frac{b_m s^m + \dots b_1 s + b_0}{a_n s^n + \dots a_1 s + a_0} \quad (m, n = 1, 2, \dots) \quad (12)$$

Coefficients a_i and b_i are decided from the parameters of each component. The design objective G_s of the steering feeling shown in the **Section 4.1** and transfer function G_a of this model are compared. In this way, the target parameter values of each element part design are quantitatively estimated.

Moreover, it is important to provide quantitatively the target parameter values of each component to the time response characteristic. For example, the inertial and viscous influences in equations (3)-(11) can be excluded for very small steering speeds and steering angle. At this time, it can be described that the relation between steering wheel torque T_h that is the input by the driver and rack stroke X_r that is the output to the vehicle is equation (13).

$$X_r(t) = \frac{1}{K_{rl}} \{ T_h(t) + T_m(t) - \sum f_{Ri}(\theta_i, t) \} \quad (f = \alpha, \beta) \quad (13)$$

The target parameters of each element are quantitatively estimated from this I/O relation.

4. 4 Design Process of Component Parts for Improvement of Steering Feeling

Based on the above study, the design process for optimizing the transmission characteristics of steering system element parts for steering feeling improvement is summarized below.

- (1) Treat the steering feeling sensory evaluation as a physical model for steering performance, and quantitatively estimate the target performance of the steering system.
- (2) Evaluate the influence that the transmission characteristics of the vehicle subsystem exert on the steering performance mentioned above.
- (3) Decide the physical values concerning the transmission characteristics allocated optimally to each element part as design target values for each part.
- (4) Judge the adoption of the target values above in consideration of the design condition of each vehicle.

Regarding (1) above, it is possible to clarify this by using the multivariate analysis technique explained in **Section 3.2**. Statement (2) is described in **Section 5** as an example of the comparison between the element characteristics of the steering system and those of the chassis components. About statement (3), described in **Section 6** is an example of the transmission characteristic analysis of a steering system component.

5. Evaluation of Vehicle Subsystem Transmission Characteristic Influence

The influence that the vehicle subsystem characteristic exerts on steering system performance is evaluated using a steering system strict model and the vehicle model.

Here, shown as an example is the improvement of "stable driving feeling" at the time of transitioning from cornering to straight driving. In this case, the time based integration value of the absolute yaw rate from the end of steering input is proposed as an example index for "stable driving feeling"⁽¹⁰⁾.

Figure 5 shows one example of evaluation results. The upper row shows the input steering wheel angle of 1 Hz sinusoidal waveform and the lower shows yaw rate of the vehicle. The time based integration value from the end of steering to settled yaw rate (shaded area) is 0.55 (deg).

The vehicle system and components that influence the dynamic yaw rate characteristic have been extracted by factor analysis. **Table 4** shows the main component characteristics. To quantify the influence on the yaw rate integration value of these elements, numerical analysis was done. A general four-wheel model⁽¹¹⁾ is adopted and the steering system element part characteristics shown in **Table 4** are considered.

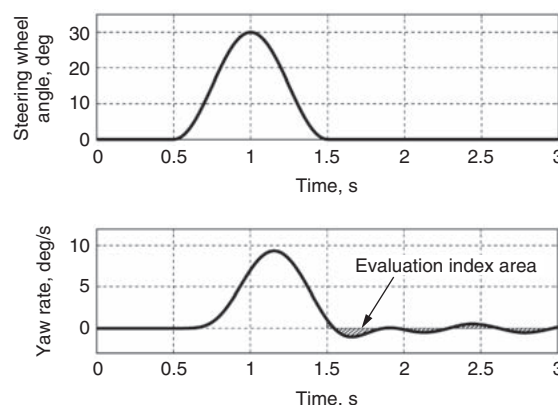


Fig. 5 Input conditions and evaluation index

Table 4 Model parameters

Vehicle subsystem	Elemental characteristic
(i) Steering	· Refer Fig. 3
(ii) Chassis	· Roll (Inertia, viscous, stiffness) · Pitch (Inertia, viscous, stiffness) · Change of load · Change of toe angle with suspension stroke · Compliance-steer characteristic
(iii) Tire	· Cornering force · Camber thrust
(iv) Vehicle	· Front axle load, rear axle load · Yaw moment of inertia · Height of gravity center · Wheel base · Track

As an improvement of yaw rate characteristics by the modification of steering system element characteristics (**Table 4-i**), viscosity C_r at the rack and elasticity K_i of the intermediate shaft has been increased. **Figure 6** (B) shows the results of this analysis. Moreover, the toe angle deviation according to the vehicle movement of roll direction has been decreased as an improvement by the modification of chassis component characteristics (**Table 4-ii**). **Figure 6** (C) shows the results of this analysis.

In the yaw rate integration value from **Fig. 6** that is a guideline for evaluation, the value in case (A) before improvement is 0.55 (deg). After modification of the characteristic, it is 0.41 (deg) in case (B) and 0.38 (deg) in case (C). This shows the possibility to improve the "stable driving feeling" by the characteristic modification of either the steering system or chassis components.

However, in the case of (B) that the steering system characteristics are modified, it takes longer from the end of the time the steering wheel angle becomes 0 to the time the yaw rate becomes 0. This means there is

possibility the vehicle response to steering operation will be evaluated as slow.

This example shows that physical characteristic modeling of steering system performance makes it possible to evaluate accurately the influence that the transmission characteristics of the vehicle subsystem exert on steering feeling. This procedure allows us to decide the best way to improve steering feeling considering the trade off issue by modification of physical characteristics parameters.

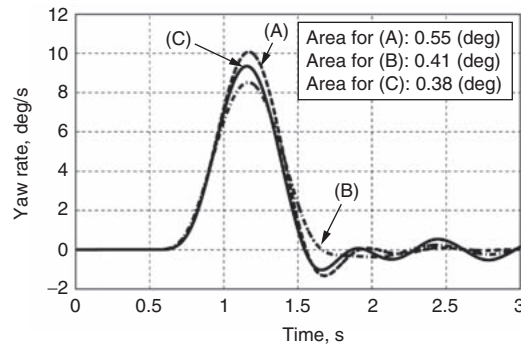


Fig. 6 Comparison of yaw rate

6. Optimization of Transmission Characteristics of Steering System Components

The optimization of physical values related to transmission characteristics of steering system components using the strict model of the steering system are shown below.

6.1 Target Characteristic of Steering Components

Shown is an example of the characteristics model to improve corrective steering operation at high-speed straight driving.

In the case of high-speed driving, the driver inputs steering angle corrective operation to the target by slightly increasing and decreasing the steering force. The driver slightly adjusts steering force based on feedback regarding the relation between steering wheel angle change $\Delta\theta_h$ that is important for high-speed driving and expected vehicle behavior deviation $\Delta\gamma$. As described in Section 4.1, a proper rack axis force ΔF_r in addition to $\Delta\gamma$ should be fed back by eyesight, etc. in order to feed back vehicle behavior deviation $\Delta\gamma$ exactly.

Quantitative target values for $\Delta\theta_h$ and ΔF_r corresponding to input torque T_h in this condition are defined as follows.

Target index A: $\Delta\theta_h$ is 0.7 deg. when T_h that is small input controllable by the driver is $1 \text{ N}\cdot\text{m}^{(1)}$. (Point A in Fig. 8)

Target index B: ΔF_r is 4 N when T_h that is small input controllable by the driver is $1 \text{ N}\cdot\text{m}$. (Point B in Fig. 9)

6.2 Analysis Result with Strict Model

The physical values related to the transmission characteristics of each element are decided as design target values of each part in the case of C-EPS[®] (Fig. 3) and the pinion shaft assistance type power steering system (P-EPS[®]).

The model of P-EPS[®] is as shown in Fig. 7. Because the only difference with the C-EPS[®] model is the position of the assistance actuator parts (③-⑤), the explanation of this model is not described in detail.

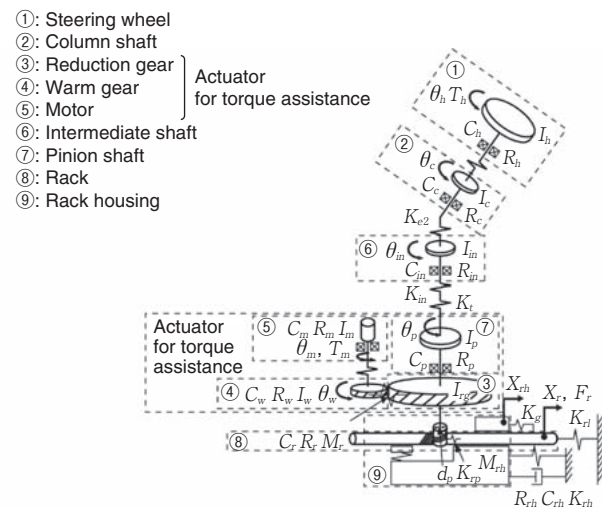


Fig. 7 Steering model (P-EPS[®])

The analysis result of characteristics between T_h and θ_h and characteristics between T_h and F_r is shown in Figs. 8 and 9 in both systems. It is understood that in both of these systems, neither index A nor B is satisfied. Moreover, the transmission characteristics are different according to the differing placement of the element parts. It is understood that P-EPS[®] is closer to the target value.

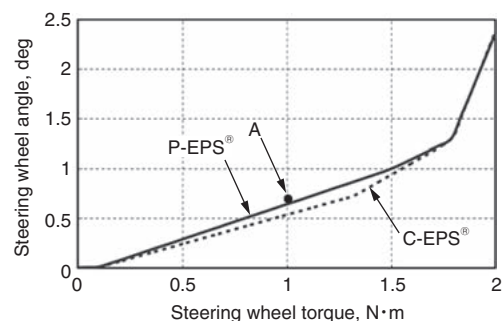


Fig. 8 Steering wheel torque - wheel angle diagram

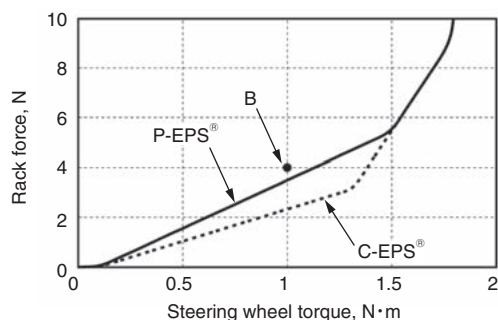


Fig. 9 Steering wheel torque - rack force diagram

6. 3 Determination of Component Characteristics Based on Analysis

An example of designing to achieve the target values with both systems is shown below. In **Figs. 8** and **9**, each flexion point and the inclination show the characteristics of main friction R_h , R_w , R_m and R_r and elasticity K_t , K_m , and K_{rp} in the steering system corresponding to ones with smaller torque to the placement of the element parts from the input side.

In C-EPS[®], index A was satisfied with about 30% decrease compared with before changing elasticity K_t (**Fig. 10**). To achieve this, various design modifications are needed, regarding such items as part strength, basic structure, and manufacturing process. On the other hand, in the case of P-EPS[®], K_t and K_m only must be decreased by about 5%. This shows it is easy to achieve index A compared with C-EPS[®].

Moreover, in regard to both C-EPS[®] and P-EPS[®], by reducing worm gear area and motor area friction (R_w , R_m) by 40%, index B was satisfied (**Fig. 11**). However, considering the actual part design, it is difficult to achieve this target with these components only, and improvement with the other element parts is needed.

It is necessary to examine the transmission characteristics of rack force input F_r from the road surface. In this case, it is necessary to optimize the transmission characteristics to steering wheel angle θ_h and torque T_h as an output to the driver in the steering system. These transmission characteristics are different because of the differing placement of element parts between C-EPS[®] and P-EPS[®].

As explained above, physical characteristics modeling of the steering system, which relates to steering performance, enables us to quantitatively design the optimal arrangement of element parts and system transmission characteristics.

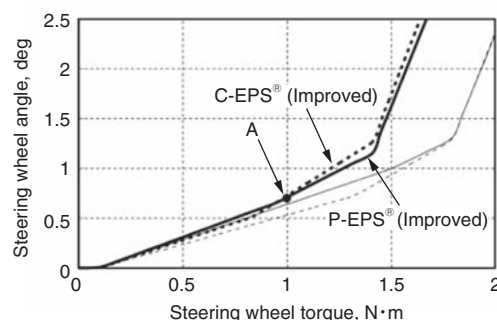


Fig. 10 Steering wheel torque - wheel angle diagram (improved)

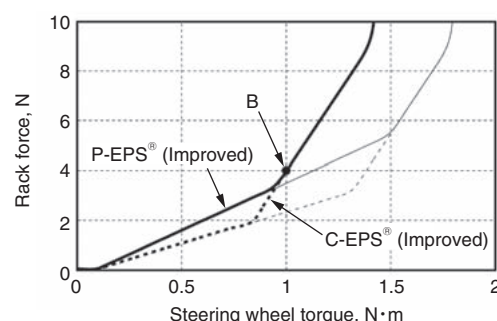


Fig. 11 Steering wheel torque - rack force diagram (improved)

7. Summary

- (1) The process by which the steering system component transmission characteristics were optimized to improve steering feeling was described.
- (2) The technique for evaluating the influence of the vehicle subsystem transmission characteristics on steering system performance was described.
- (3) The technique for determining physical values concerning the transmission characteristics allocated optimally to each component as design target values for each part was described.

8. Conclusion

The transmission characteristics of each element part to optimize all steering feeling features at the same time are not provided as single values. However, the system performance can be optimized by providing the physical values in which the transmission characteristics of each element part are shown according to the target of steering feeling and allocating them appropriately. The process for the design of the steering system element parts according to each physical value will be clarified in the near future.

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