Research on Haptic Generating Control Law for SBW by Impedance Control Using Model Matching Assumed Shared Control Usage

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***Abstract*—Regarding HMI (Human Machine Interface) related research on automatic driving, the safety, driver acceptability, and transporter function research on domestic demand is a trend. Originally, Vehicle means a vehicle that a person manipulates, which means an aircraft, a car, a bicycle, or a ship. In the HMI related research on automatic driving, there are few research on the interaction between HMI that has made this basic function (driving pleasure) explicit. The reason is that the aim to drive a car is young and old and weak, the skill and the use of the car are all different, and it is enclosed with the greatest common denominator that is safe rather than responding to it individually. It is SBW (Steer By Wire), SAS (Stability Augmentation System), CAS (Control Augmentation System) that realize it, and these are configured MM (Model Matching), State Observer, Haptic Generating (Tactile feeling). Furthermore, when switching from automatic operation to manual operation, whether to be able to transition from automatic operation to manual operation safely becomes a problem. Proposed steering control system, by model matching, the steering reaction force desired response is realized by linear combination of the impedance (Inertance, Mobility, Stiffness) of the steering mechanism (generation of a haptic queue) model. We have developed and implemented the Haptic Generating steering mechanism in the steering reaction mechanism of the HMI evaluation simulator which remodeled the small car. Autonomous driving has been polarized, with one aiming at advanced automated driving levels 4 and 5 for commercial vehicles (such as trucks responsible for logistics) and the other being shared control based on partial driving automation level 2 for personal vehicles. This is a development aiming to fun driving a car together such as human and horse. We are studying not only HMI (Human Machine Interface) but also stability and robustness of vehicle control system for the latter shared control. On this paper, we report on the feasibility of haptic control by impedance control as a result of research on the authority transfer method to shift from automatic operation to manual operation of shared control, which is integrated with haptic control by impedance control.**

***Index Terms*—haptic control, model matching, shared control, impedance control, HMI**

I. INTRODUCTION

Initially, in relation to research related to HMI related to autonomous driving, in the academic congress, manufacturer, and social consensus, safety, driver acceptance, rather than a discussion of the basic function that a car is a controlled object that is integrated with humans research on the safety, driver acceptability and transporter function [1]-[4] were dominant.

On the other hand, according to the recommendation of the Subcommittee on Autonomous Driving [5], there are many images of fully automatic driving or unattended automatic driving, and many people think that this will be realized early.

What has been marketed so far and what is being developed by manufacturers for the time being is only partially automatic operation (semi-automatic operation) called Level 2, which is premised on the driver's responsibility. On the other hand, the automatic movement of cars leads to new innovations in movement, and also to movements aimed at new ecosystems such as urban and lifestyle changes.

Against this background, shared control is more than the automatic driving level definition [6] for the social perception of automatic driving. It has come to propose what can be said "Human-horse integration" so-called "Jimba Ittai" to be a development form of automatic driving technology.

Therefore, automated driving has been polarized, with one aiming at advanced automated driving levels 4 and 5 for commercial vehicles (such as trucks responsible for logistics) and the other being shared based on partial driving automation level 2 for private vehicles. This is a development aiming at control (use for enjoying driving a car).

It has also been suggested that the existence value of level 3 disappears. [7]

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We are researching not only HMI (Human Machine Interface) but also stability and robustness of vehicle control systems for the latter shared control.

Originally, vehicle means a vehicle that is maneuvered by humans, and refers to aircraft, automobiles, bicycles, and ships. In HMI-related research related to automatic driving, there is almost no research on the interaction between HMI that makes this basic function (Joy of driving, “Fun to drive”, “Be a driver” *etc.*) explicit.

The reason is that the target of driving a car is young and old, and the skill and use of the car are different. This is something you can't do with mass-produced products.

On the other hand, pilots who fly in fighter aircraft have high skills and limited uses, so a very high level of HMI has been researched and put to practical use.

Although it is not possible to simply compare the two, even in the case of automobiles, it is necessary to research the basic performance of a Human-Horse Integration as potential, even if it does not come out explicitly.

SBW (Steer By Wire), SAS (Stability Augmentation System), and CAS (Control Augmentation System) make this possible, which can be composed of MM (Model Matching), state observer, and Haptic Generating (Tactile feeling).

Furthermore, when switching from automatic operation to manual operation, the problem is whether it is possible to safely transition from automatic operation to manual operation. In the case of an aircraft accident, there was an accident [8] that caused a crash due to repulsion of autopilot operation and pilot operation when the Chinese Airlines A300 aircraft landed.

In addition, there is a risk (risk homeostasis) [9] that exceeds the limit of the driver's maneuvering skill when the driver intentionally intervenes during the automatic driving due to overconfidence in the autonomous driving vehicle.

The proposed steering control system is based on a linear combination [10] of model matching [11] and impedance (inertance, mobility, stiffness) [12] of the steering mechanism (Haptic generation mechanism) model to realize the desired response of the steering reaction force.

In this paper, based on this result, we report a haptic generation control law by impedance control using Model Matching.

Similar research [13]-[15] that change steering reaction force (Haptic) by impedance control are angle-controlled base torque control, Torque-based type that directly feeds back torque as manipulated variable by Model Matching control.

This method has the advantage that the control law can be configured simply for angle-controlled base torque control [10], and the impedance component can be specified by pole arrangement, so it is easy to be familiar with Model Matching control.

The purpose of this research is to report the haptic control method by impedance control, which is the basic technology for haptic shared control, which is the final goal.

The following outlines our final goal, haptic shared control.

Shared control is a system in which machines and humans perform integrated control, which is subject to control based on the result of sharing the steering input from humans and the steering input from the system.

There is bilateral control as a similar concept, but this is applied in the form of a manipulator on the master (drive) side and a manipulator on the slave (driven) side, which distributes the control between the drive side, the driven side, and the human-machine to be fixed the authority.

On the other hand, shared control is a system in which the cooperative state of the authority side, the driven side, and the authority ratio transitions. There is an example [16] that expresses the cooperative state in a two-dimensional state with each axis of the subject's location and the coincidence of intention.

In our haptic shared control, we envision a three-dimensional state transition diagram with an added haptic control axis as a guideline to indicate the cooperative state.

Fig. 1 shows an example (driver initiative state). This figure is useful for visualizing the cooperative state of the driver and the vehicle and associating sensory evaluation with design parameters (impedance).

The steering power [17] on the horizontal axis (front side) in Fig. 1 is steering torque × steering angular velocity, and represents the energy consumed by the driver per unit time for steering, and the driver fatigue accumulated over time. Since the degree is used as a sensory criterion, it is considered appropriate as an HMI evaluation index.

The vertical axis shows the output power of the Haptic motor, and the color bands show the impedance (inertance, mobility, stiffness) components.

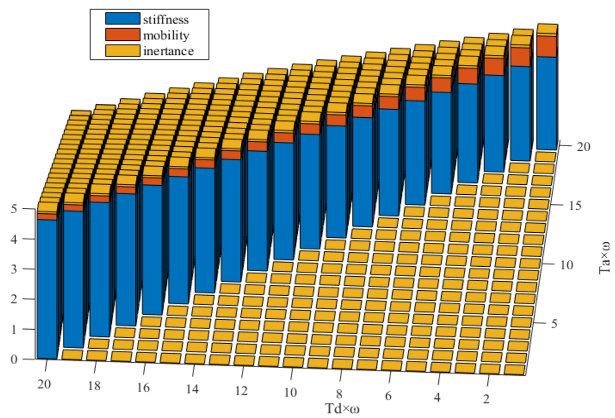


Figure 1. This transition curve shows the authority variation. Vertical axis shows the differential power, Horizontal (this side) axis shows the driver steering power and Horizontal (the other side) axis shows the system steering power of Haptic.

II. Steering Haptic Generation Control Using Impedance Control

A. Control Law of Steering Haptic Generation Mechanism

The control law of the steering haptic generation mechanism shown in the mechanism of SBW Type3 [18] shown in Fig. 2 is discussed in Section *B* and below. The generation mechanism is composed of the followings.

(1) Steering Haptic desired response according to the driver's steering torque is generated by linear combination of impedance (inertance, mobility, stiffness). [10], [12]

(2) Realize desired response characteristics for the difference between steering torque and Haptic torque by model matching (MM) control.

(3) There is a research [19], [20] that discusses the steering angle input and the steering torque input independently, but the steering torque in this research is steering angular acceleration (inertance) (Mobility) and dynamic torque by linear combination of steering angle (stiffness). [21]

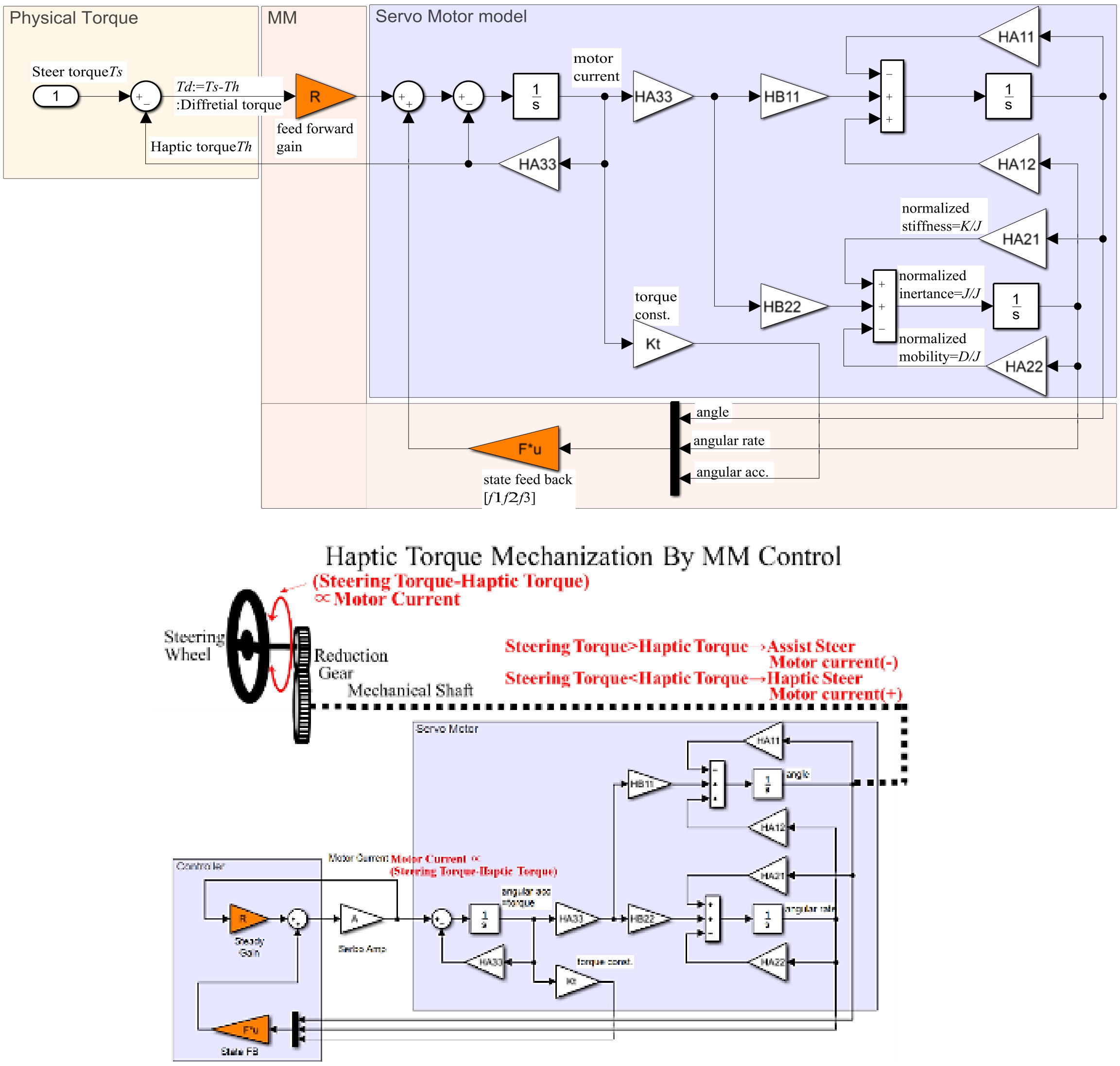


Figure 2. The upper side figure shows mechanization block indicated the relationship MM (Model Matching) control and the servo motor model. The lower side figure shows mechanization block imaged to actual architecture. Table I shows the Nomenclatures/ Specification of mechanization and hardware.

B. Correlation between Impedance Control and MM Control (Desired Pole Placement)

1) Impedance control

The difference Td between the steering torque and the Haptic torque is given by equation (1).

$$T_d = T_s - T_h \tag{1}$$

where,

T_s : Steer torque by driver, T_h :Haptic torque

In a steering mechanism in which a conventional steering and tie rod mechanism are mechanically coupled, Haptic torque is mainly generated by self-aligning torque. [22]

The difference T_d between the steering torque and the Haptic torque is expressed by a linear combination of impedance (inertance, mobility, stiffness) as shown in equation (2).

The haptic control law is a control law that obtains the desired haptic (steering response) by changing this impedance to the desired response by MM control.

$$\begin{aligned} &T_d = J_c\dot{\omega} + D_c\omega + K_c\theta \\ &\text{where,} \\ &J_c : \text{Inertance of covetional mechanism} \\ &D_c : \text{Mobility of covetional mechanism} \\ &K_c : \text{Stiffness of covetional mechanism} \end{aligned} \tag{2}$$

2) Model Matching (MM) control

Equation (3) shows the equation for state of the servo motor controlled by MM control, and Table I shows the specifications.

TABLE I. NOMENCLATURES/ SPECIFICATION OF MECHANIZATION AND HARDWARE

θ	Angle of motor output shaft	State variable
ω	Angular rate of motor output shaft	
$\dot{\omega}$	Angular acceleration of motor output shaft	
f_1	Feedback gain of angle	State feedback gain
f_2	Feedback gain of angular rate	
f_3	Feedback gain of angular acceleration	
T_m	Motor torque(rated)	94.9 mN·m
i	Reduction gear ratio	3.2
J_{sw}	Normalized inertia moment of steering shaft	1 kgm^2
K_t	Torque constant	16.4 mN·m/A
HA_{11}- HA_{22},HA_{33}	Contents of motor system matrix	[0 1; -1 2],10
HB_{11}, HB_{22}	Contents of motor input vector	[0;1]

MM control defines the reference command value *ref.*, control input *u*, controlled output *y*, and state variables *x* for the control plant *G* (s) (servo motor), as well as state feedback law *F* and feedforward law *R* which is a control law that obtains the desired target response of *ref.* → *y* by *R*. The parameters of plant are hardware specific and basically constant (time invariant).

By adding MM control to the plant and arbitrarily changing the pole arrangement of *F*, we decided to obtain the desired response of *ref.* → *y*. Furthermore, the steady-state gain (*y / ref.*) can always be set to 1 (0dB) by *R*.

Equation (4) shows the state equation for the closed-loop control system (fundamental controller) with MM control.

The hardware-specific impedance **A** matrix shown in equation (3) can be changed to the desired impedance by the $\mathbf{A_f} = \mathbf{A} + \mathbf{BF}$ matrix as shown in equation (4). In other words, the desired haptic response can be obtained.

$$\left.\begin{aligned} &\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}u \\ &y = \mathbf{C}\mathbf{x} \\ &\text{where,} \\ &\mathbf{x} := \begin{bmatrix} \theta \\ \omega \\ \dot{\omega} \end{bmatrix},\ \mathbf{A} := \begin{bmatrix} HA_{11} & HA_{12} & HB_{11} \\ HA_{21} & HA_{22} & HA_{33}\times HB_{22} \\ 0 & 0 & HA_{33} \end{bmatrix} \\ &\mathbf{B} := \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \mathbf{C} := \begin{bmatrix} HC_1 & HC_2 & 0 \end{bmatrix} \\ &HA_{11} \equiv 0, HA_{12} \equiv 1 \\ &HA_{21} = -\frac{K}{J}, HA_{22} = \frac{D}{J}, HA_{33} = K^{\forall} \\ &HB_{11} \equiv 0, HB_{22} \equiv \frac{1}{J} \\ &HC_1 \equiv 1, HC_2 \equiv 0 \\ &\theta : \text{Motor output angle} \\ &\omega : \text{Motor output angular rate} \\ &\dot{\omega} : \text{Motor output angular acceleration} \\ &J : \text{Inertance} \\ &D\text{:Mobility} \\ &K\text{:Sttifness} \\ &K^{\forall} : \text{Arbitrary Constant of Haptic torque} \end{aligned}\right\} \tag{3}$$

$$\left.\begin{aligned} &\text{MM (Foundamental)controller} \\ &\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}u \\ &\text{replace } u := Rr + \mathbf{F}x \\ &\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}(Rr + \mathbf{F}x) \\ &\quad = (\mathbf{A} + \mathbf{BF})\mathbf{x} + BRr \\ &\therefore \dot{\mathbf{x}} = \mathbf{A_f}\mathbf{x} + BRr \\ &\text{where,} \\ &\mathbf{A_f} := \mathbf{A} + \mathbf{BF} \\ &y = \mathbf{C}\mathbf{x} \\ &\mathbf{F} = \begin{bmatrix} f_1 & f_2 & f_3 \end{bmatrix} \\ &R = -(\mathbf{C}\mathbf{A_f^{-1}}\mathbf{B})^{-1} \\ &f_1 : \textit{Feedback gain ofangle} \\ &f_2 : \textit{Feedback gain ofangular rate} \\ &f_3 : \textit{Feedback gain ofangular acceleration} \end{aligned}\right\} \tag{4}$$

C. Measuring Method of Actual Servo Motor Status

The angle θ [rad], angular velocity ω [rad / s], and angular acceleration ($\propto$torque) $\dot{\omega}$ [rad / s^2], which are state variables necessary for MM control, are measured from the actual servo motor.

The angle θ was obtained from the encoder output of the motor, and the angular velocity ω was obtained from the measured logging value of the motor driver.

The angular acceleration (torque / moment of inertia) $\dot{\omega}$ is expressed as shown in equation (5), where J_m = 1 is the torque obtained by multiplying the measured motor current by the torque constant in front of the input to extract it as a state variable which is defined as normalized (generalized) impedance. [10]

Since this normalized impedance is extracted as a state variable, it can be balanced with the input torque as the actual torque by multiplying it with the state feedback coefficient. After that, the normalized impedance is converted to the real impedance by equation (6). Fig. 3 shows the relationship between the pole assignment specified by MM control and the impedance element.

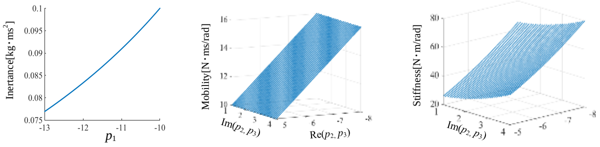


Figure 3. Left side figure is the inertance diagram. Middle figure is the mobility diagram. Right side figure is the stiffness diagram.

The correlation between each impedance and pole arrangement is shown below.

By grasping this correlation, it becomes possible to quantitatively and systematically define the haptic correction to the driver's HMI evaluation comments.

(1) Impedance including inertance can be controlled by changing the pole arrangement p_1. However, since inertance is normalized by J_m (see equation (5)), inertance alone cannot be controlled independently by p_1.

(2) Mobility can be controlled by changing the real components of the pole assignments p_2 and p_3.

(3) Stiffness can be controlled by changing the real and imaginary components of the pole assignments p_2 and p_3.

$$\left.\begin{aligned}
&T_m = J_m \times \dot{\omega} = I_m \times K_t \Rightarrow T_m = I_m \times K_t \equiv \dot{\omega}\\
&P(s) = \frac{\tau_m}{s+\tau_m} \times \frac{1}{\tau_m\left(J's^2 + D's + K'\right)} = \frac{\frac{1}{J_m}}{s+\frac{1}{J_m}} \times \frac{1}{\frac{1}{J_m}\left(J's^2 + D's + K'\right)}\\
&= \frac{\frac{1}{J_m}}{s+\frac{1}{J_m}} \times \frac{1}{\frac{J'}{J_m}s^2 + \frac{D'}{J_m}s + \frac{K'}{J_m}} = \frac{\frac{1}{J_m}}{s+\frac{1}{J_m}} \times \frac{1}{Js^2 + Ds + K}\\
&\text{where,}\\
&J = \frac{J'}{J_m}, D = \frac{D'}{J_m}, K = \frac{K'}{J_m}\\
&J', D', K' : \text{A priori Impedance}\\
&T_m : \text{Mesurement toruque of Haptic motor}\\
&J_m = \frac{1}{\tau_m} : \text{Specified Inertia moment of Haptic motor mechanism}\\
&\tau_m : \text{Time constant of Haptic motor mechanism}\\
&I_m : \text{Mesurement current of Haptic motor}\\
&K_t : \text{Torque constant}\\
&P(s) : \text{Transfer function of Haptic motor}
\end{aligned}\right\} \quad (5)$$

$$\left.\begin{aligned}
&P_{MM}(s) = \frac{HA_{33}}{s+HA_{MM}} \times \frac{1}{HA_{MM}\left(\frac{J'}{HA_{MM}}s^2 + \frac{D'}{HA_{MM}}s + \frac{K'}{HA_{MM}}\right)}\\
&= \frac{\frac{HA_{33}}{HA_{MM}}}{s+HA_{MM}} \times \frac{1}{\frac{J'}{HA_{MM}}s^2 + \frac{D'}{HA_{MM}}s + \frac{K'}{HA_{MM}}} = \frac{k}{s+HA_{MM}} \times \frac{1}{J_a s^2 + D_a s + K_a}\\
&\text{where,}\\
&P_{MM} : \text{Plant model after MM,}\\
&HA_{MM} : \text{Actuator cut off frequncy after MM,}\\
&J_a, D_a, K_a : \text{Actual impedance, } J_a = \frac{J'}{HA_{MM}}, D_a = \frac{D'}{HA_{MM}}, K_a = \frac{K'}{HA_{MM}}
\end{aligned}\right\} \quad (6)$$

III. Preliminary Confirmation of Feasibility by HILS

HILS (Hardware In the Loop Simulation) for evaluation was constructed using the steering haptic generation mechanism designed in Chapter II. The evaluation HILS consisted of a steering haptic generation mechanism to be evaluated and a measurement signal logger.

This time, preliminary confirmation was made about the feasibility of haptic control by impedance control rather than sensory evaluation.

A. Experimental Conditions

Table II shows the conditions in the control law confirmation experiment of the steering haptic generation mechanism. Haptic desired response impedance is shown from the pole arrangement and equation (5).

B. Confirmation Results

Confirmation result Control law confirmation experiment of steering haptic generation mechanism according to Table II is performed by impedance waveform (Fig. 4) and steering power (fig. 5, steering torque x steering angular velocity, referred to as steering horsepower in reference. [17]). The impedance waveform is changed by the pole arrangement. The feasibility of the control law was confirmed.

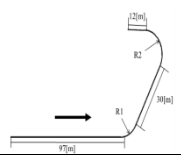
By Fig. 4, it can be seen that the impedance (linear combination of inertance, mobility, and stiffness) differs for each condition in Table II, and that the impedance is controlled as follows according to the pole placement of the MM control.

(1) As shown in Fig. 4 (left) and Fig. 4 (middle), the entire impedance can be controlled by changing the real component of the pole arrangement p_1.

(2) As shown in Fig. 4 (middle) and Fig. 4 (right), the stiffness ratio with respect to the entire impedance can be controlled by changing the imaginary components of the pole assignments p_2 and p_3.

The steering energy, which is the integral value of the steering power in Fig. 5 (left), is calculated to be 1.42 kJ, the steering energy in Fig. 5 (middle) is 1.54 kJ, and the steering energy in Fig. 5 (right) is 1.71 kJ. 5 (left) has the smallest steering energy and good trajectory. This shows that the consumption of steering power (steering energy) can be controlled by the haptic reaction force due to the pole arrangement.

TABLE II. MM Method Condition

Conditions \ Case		1	2	3
Pole placement	p_1	-10	-11	-11
	p_2	-5+3i	-5+3i	-5+4i
	p_3	-5-3i	-5-3i	-5-4i
Impedance	Inertance[kg·ms^2]	0.100	0.091	0.091
	Mobility[N·ms/rad]	1.000	0.909	0.909
	Stiffness[N·m/rad]	3.400	3.091	3.727
Ref. Trajectory Profile	J-turn (Straight=97 m) (R1=15.6 m) (Straight2=30 m) (R2=15.4 m) (Straight3=12 m) 			
Velocity	25 km/h			

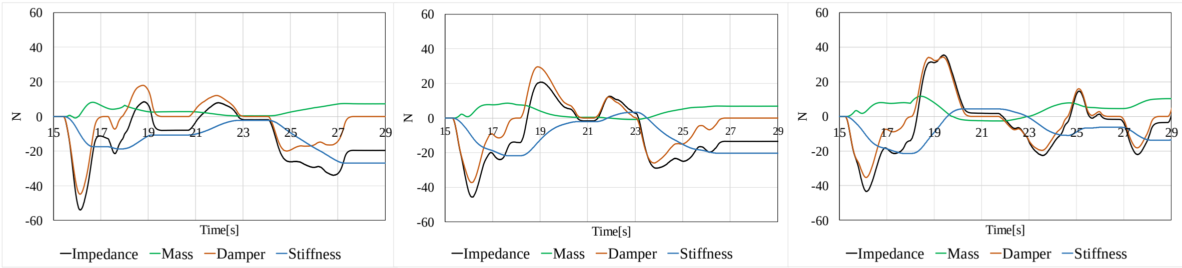


Figure 4. Left side figure is the impedance waveform of Case 1 in Table II. Middle figure is the impedance waveform of Case 2 in Table II. Right side figure is the impedance waveform of Case 3 in Table II. The impedance waveform is changed by the pole arrangement.

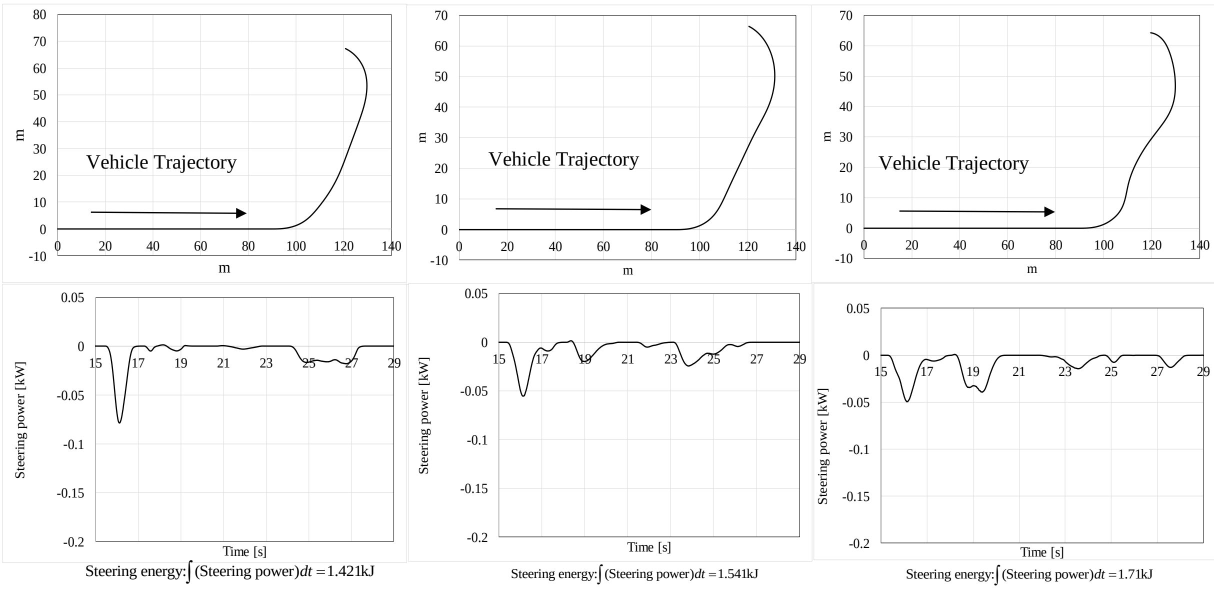


Figure 5. Trajectory simulation result and Steering Power diagram. Left side figure is Case 1 in Table II. Middle figure is Case 2 in Table II. Right side figure is Case 3 in Table II. Steering power is different in each case. This is considered to be different Haptic in each case.

IV. Conclusion

This time, a haptic generation steering mechanism was developed and implemented in the steering reaction mechanism of the HMI evaluation simulator that was modified from a small car. This is a torque-based type that directly feeds back torque as a manipulated variable by Model Matching control, and has the advantage that the control law can be configured simply for angle-controlled base torque control, and the impedance component can be specified by pole placement. The following effectiveness was confirmed by matching control.

(1) Haptic reaction force was generated by impedance control.

(2) As a generalized impedance, we developed a mechanism that can observe normalized inertance as a state quantity, and was able to measure the difference between driver steering torque input and Haptic torque without using a torque sensor.

(3) Impedance control of torque-based control was realized.

(4) The Haptic reaction force was realized by the pole arrangement of the basic controller (MM). The relationship between the pole placement and the impedance was systematically analyzed.

(5) In the future, we plan to optimize the impedance component by sensory evaluation and incorporate it into the sharing controller based on this result.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Dr. yang organized research promotion, Dr. Takahata conducted research planning, Ms. Yasuzumi conducted HMI research, and main author Ota carried out research promotion.

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