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(54) **FOUR-WHEEL STEERING SYSTEM**

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(57) **ABSTRACT**

The four-wheel steering system includes a rear-wheel steering system that steers rear wheels of the vehicle in accordance with a steering angle of a steering wheel. When the vehicle speed is lower than a vehicle speed threshold, the rear-wheel steering system steers the rear wheels in an opposite direction to that in which the front wheels are steered. When the vehicle speed is lower than the vehicle speed threshold, the rear-wheel steering system sharply increases the rate of increase in target steered angle of the rear wheels with respect to an increase in steering angle when an absolute value of the steering angle is equal to or larger than an absolute value of an angle threshold. The front-wheel steering system has a motor that is a source of a steering assist force and a first ECU that controls the motor in accordance with the steering state.
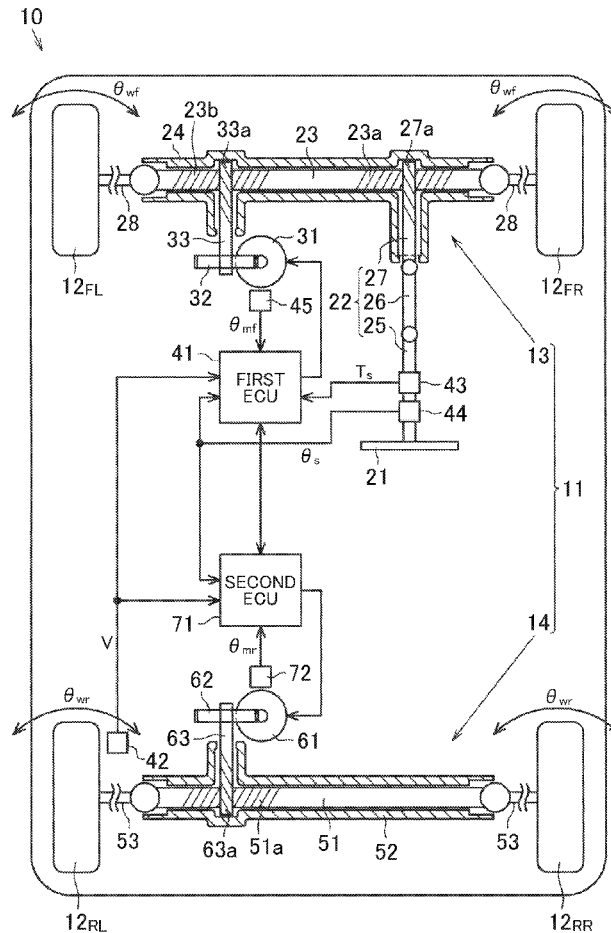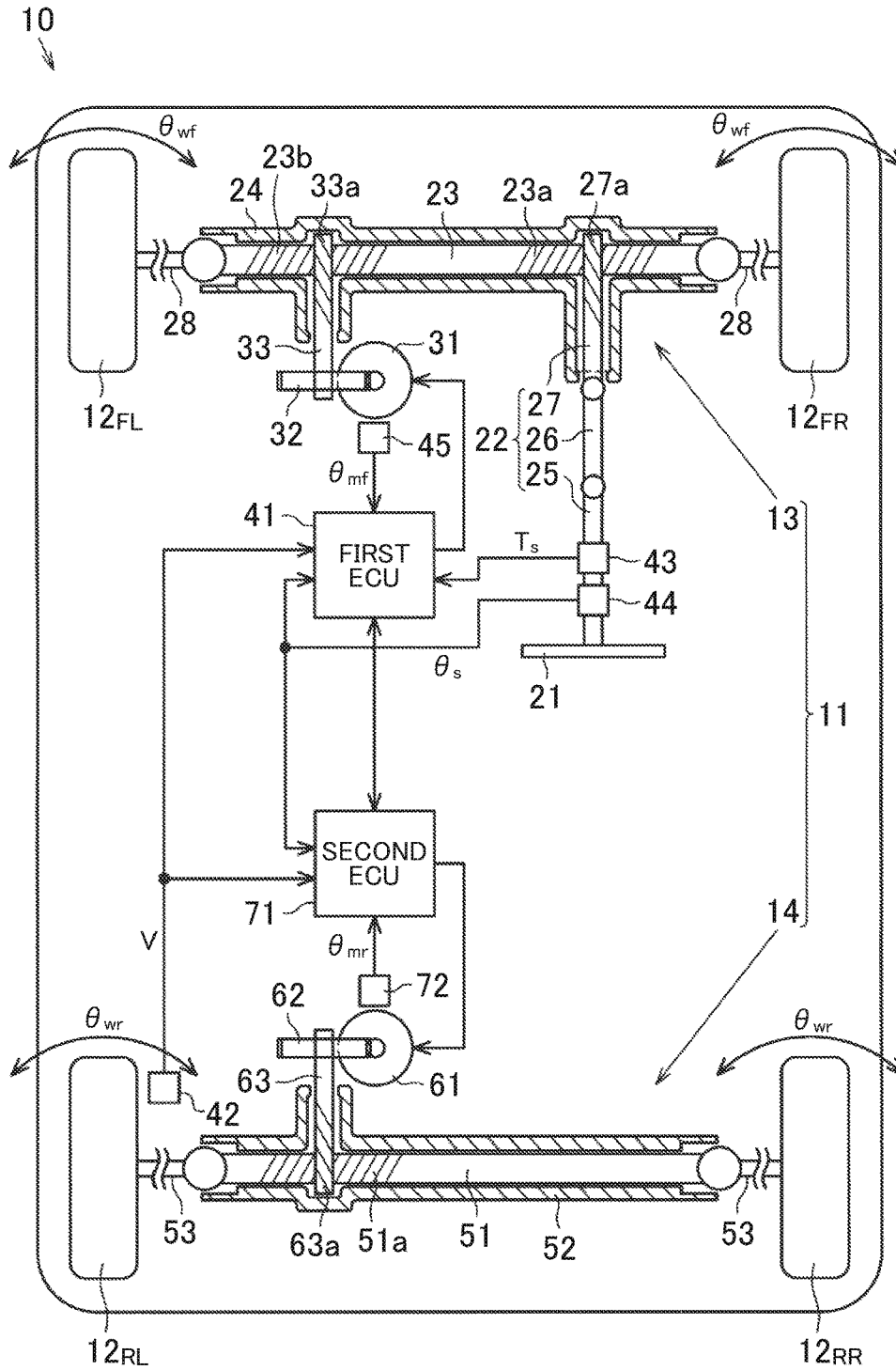
FIG. 1

FIG. 2
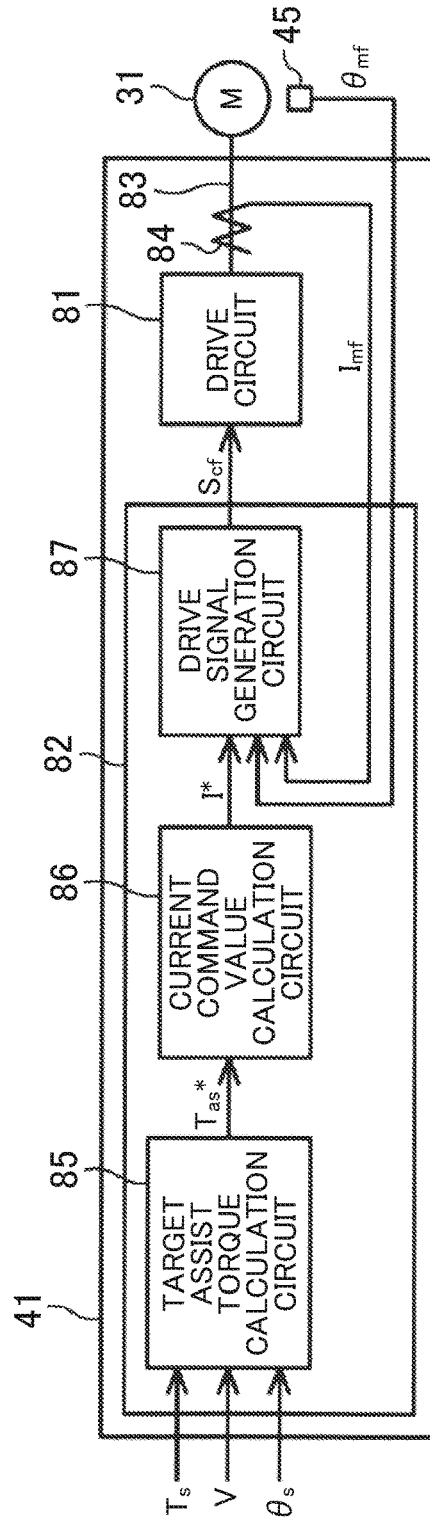
FIG. 3
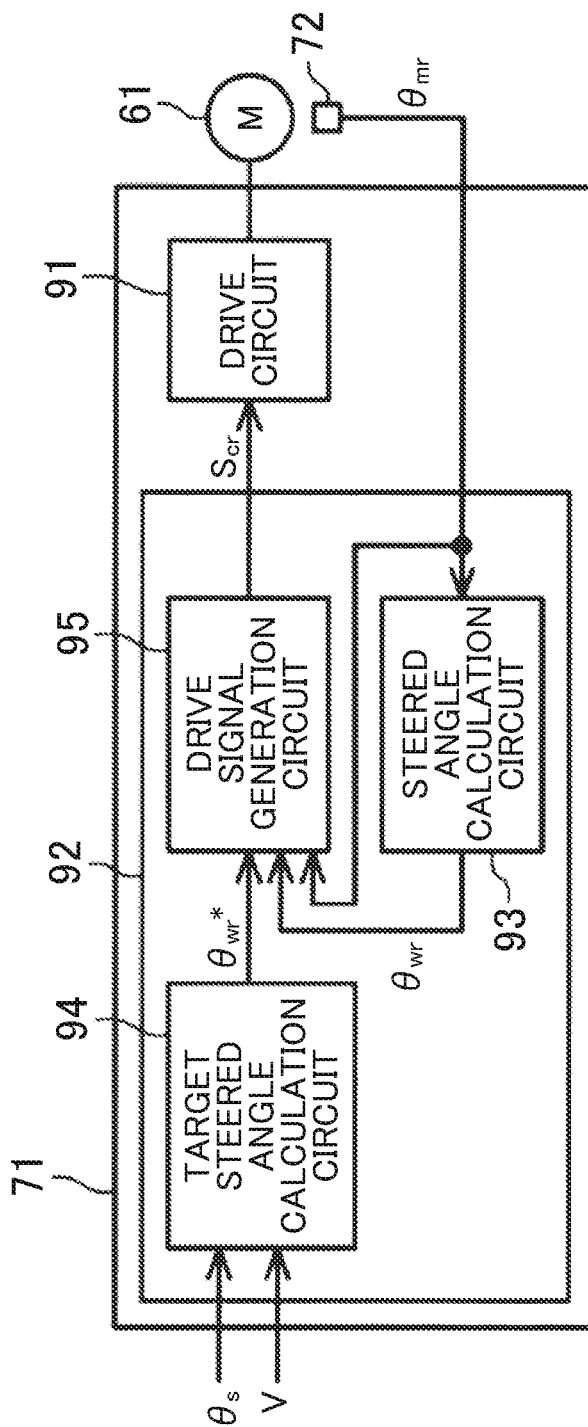
FIG. 4A
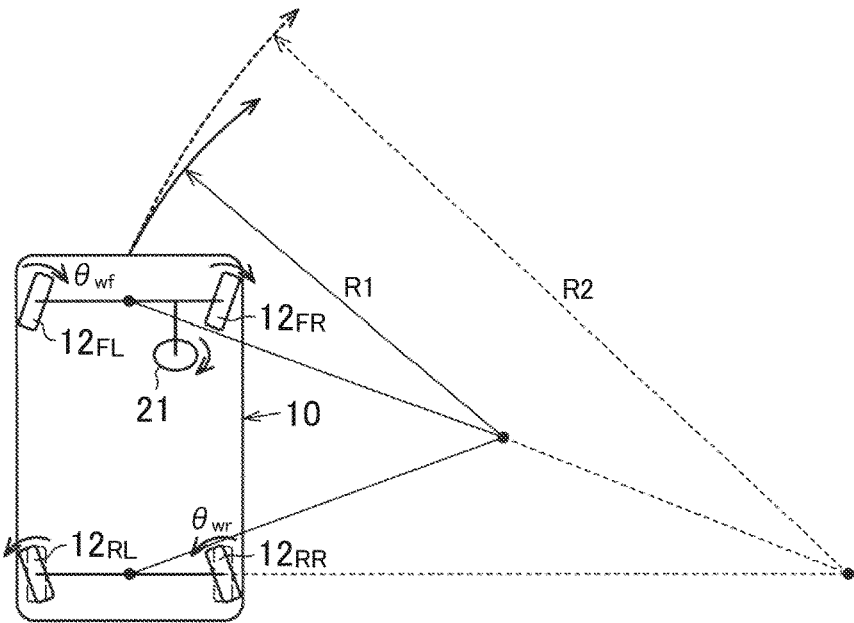
FIG. 4B

$FIG.5$

GRAPH A

T_s

$-\theta_{th}$

$-\theta_{max}$

0

θ_{th}

θ_{max}

θ_s

M1

GRAPH B

$\theta_{wr}{}^*$

$-\theta_{th}$

$-\theta_{max}$

0

θ_{th}

θ_{max}

θ_s

GRAPH C

R

$-\theta_{max}$

$-\theta_{th}$

0

θ_{th}

θ_{max}

θ_s

FIG.6

FIG.7

$FIG.8$

GRAPH A

T_s

$-\theta_{th}$

$-\theta_{max}$

0

θ_{th}

θ_{max}

θ_s

GRAPH B

$\theta_{wr}{}^*$

M2

FIRST CHAR-
ACTERISTICS

SECOND CHAR-
ACTERISTICS

$-\theta_{th}$

$-\theta_{max}$

0

θ_{th}

θ_{max}

θ_s

GRAPH C

R

$-\theta_{max}$

$-\theta_{th}$

0

θ_{th}

θ_{max}

θ_s

F I G . 9

$V \leq V_{th}$

START

S101

OBSTACLE
DETECTED?

NO

YES

USE STEERING
CHARACTERISTICS
MAP M2

S103

USE STEERING
CHARACTERISTICS
MAP M1

S102

END
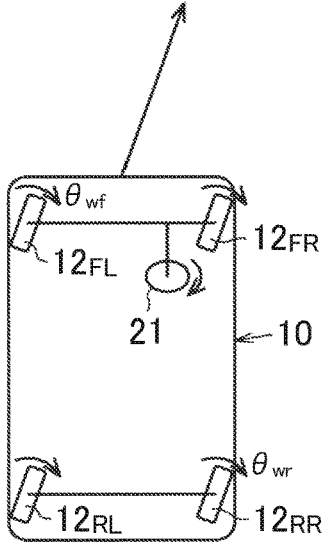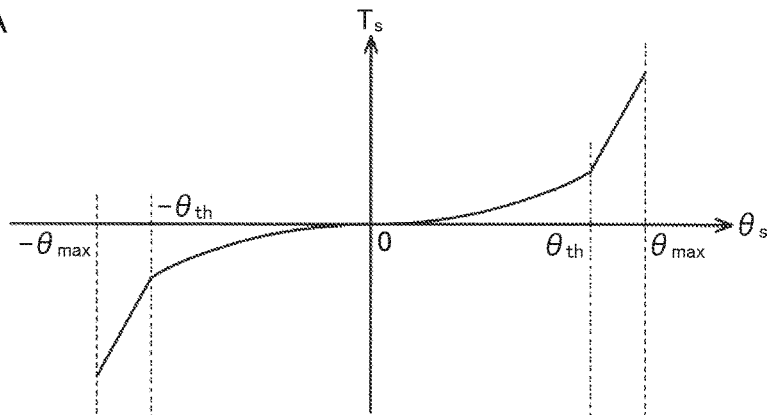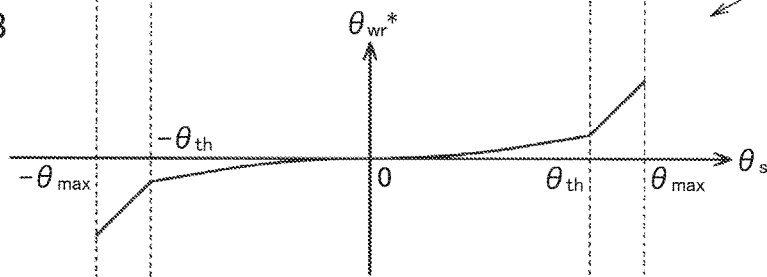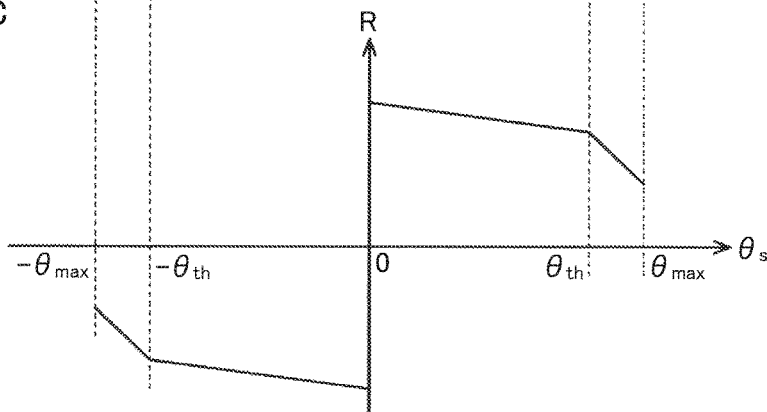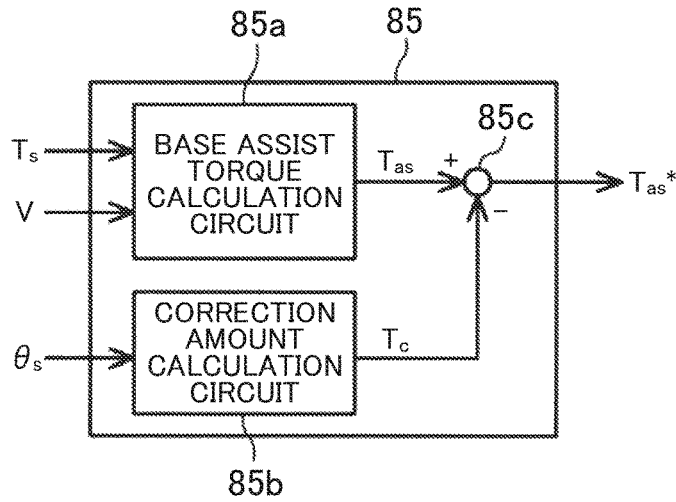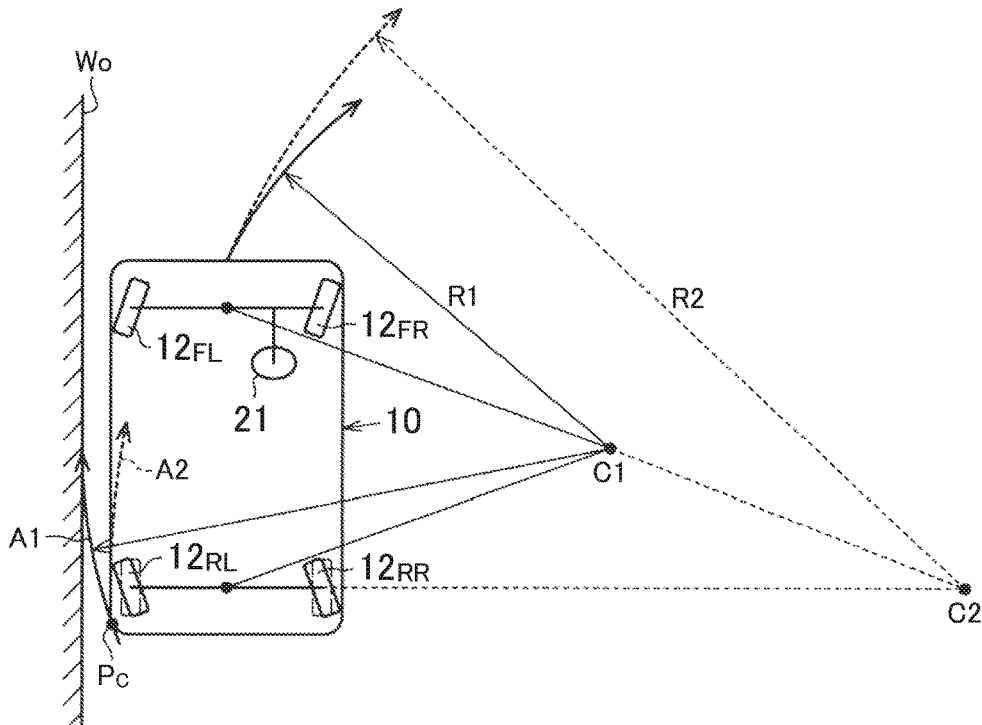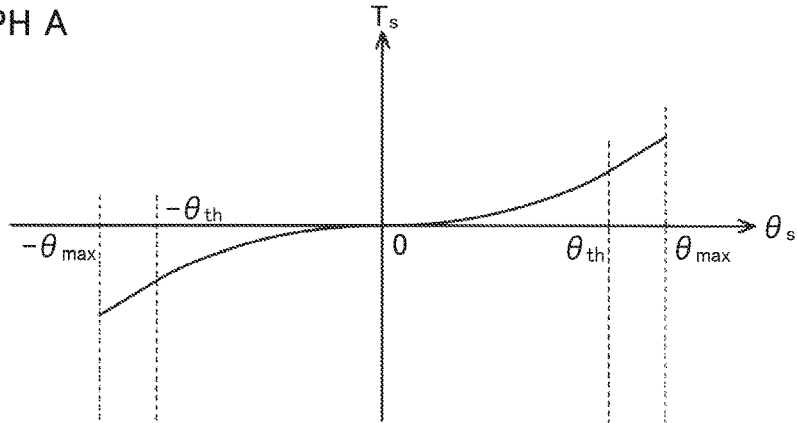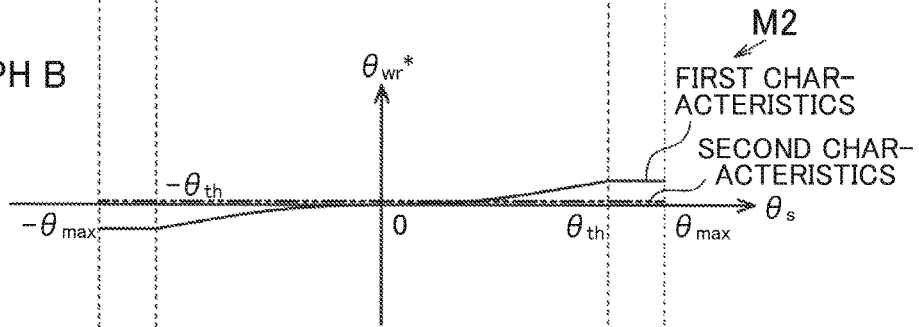
FIG. 10

FOUR-WHEEL STEERING SYSTEM

[0001] The disclosure of Japanese Patent Application No. 2018-076131 filed on Apr. 11, 2018 including the specification, drawings and abstract, is incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0002] The invention relates to four-wheel steering systems.

2. Description of the Related Art

[0003] As described in, e.g., Japanese Patent Application Publication No. 2014-213775 (JP 2014-213775 A), four-wheel steering systems that steer not only front wheels but also rear wheels of a vehicle in accordance with operation of a steering wheel are conventionally known in the art. When the vehicle moves at low speeds, the four-wheel steering system steers the rear wheels in the opposite direction to that in which the front wheels are steered in accordance with the steering angle of the steering wheel. This allows the driver to turn the vehicle with a smaller turning radius when, e.g., maneuvering the vehicle in a parking lot.

[0004] For example, steering characteristics of the rear wheels with respect to the steering angle can be set so that the steered angle of the rear wheels increases in proportion to an increase in steering angle. The driver need only turn the steering wheel more when he or she wants 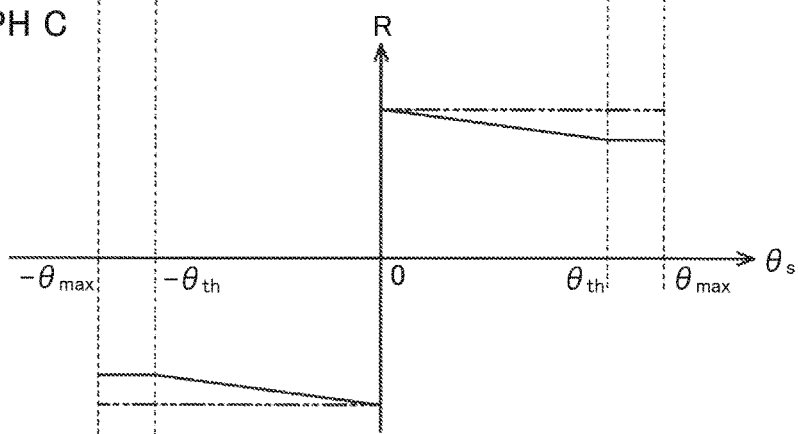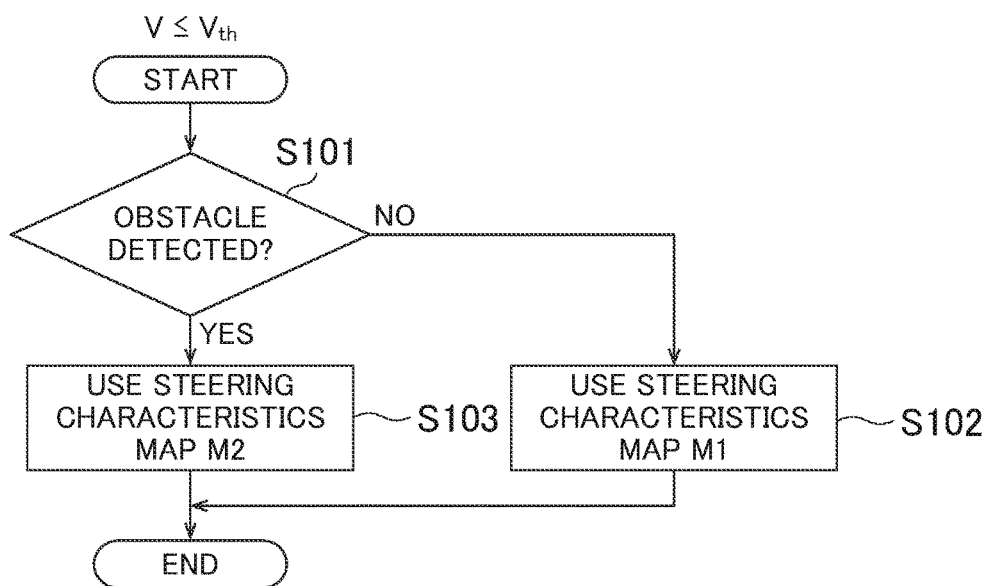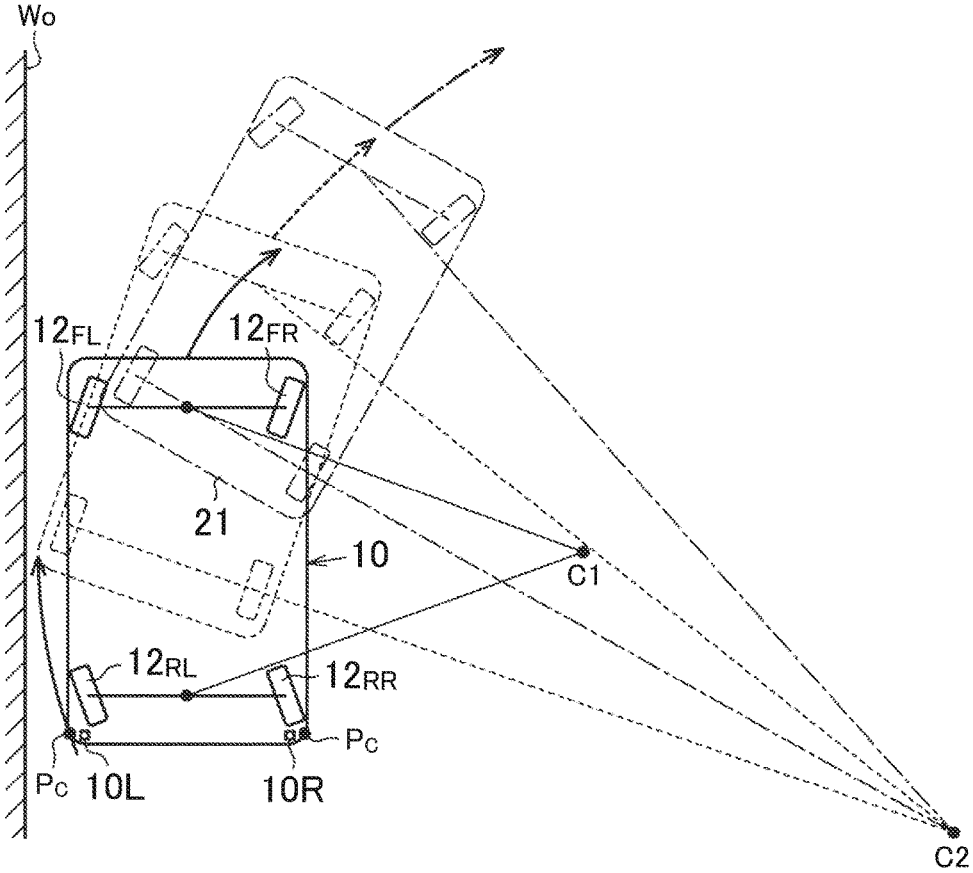to turn the vehicle with a smaller turning radius. However, the driver may not always be able to turn the vehicle as desired depending on the situations where the vehicle travels or the situations where the driver drives the vehicle, such as when parking in a garage or when driving on a narrow road bent like a crank or a U-turn road.

SUMMARY OF THE INVENTION

[0005] It is one object of the invention to provide a four-wheel steering system capable of providing better maneuverability with a small turning radius.

[0006] According to one aspect of the invention, a four-wheel steering system includes: a front-wheel steering system that steers front wheels of a vehicle; and a rear-wheel steering system that steers rear wheels of the vehicle in accordance with a steering angle that is a rotation angle of a steering wheel. When a vehicle speed is lower than a vehicle speed threshold, the rear-wheel steering system steers the rear wheels in an opposite direction to that in which the front wheels are steered. When the vehicle speed is lower than the vehicle speed threshold, the rear-wheel steering system sharply increases a rate of increase in steered angle of the rear wheels with respect to an increase in steering angle when an absolute value of the steering angle is equal to or larger than an absolute value of an angle threshold.

[0007] With this configuration, when the vehicle speed is lower than the vehicle speed threshold, a turning radius of the vehicle sharply decreases with an increase in steering angle when the steering angle is equal to or larger than the angle threshold. The vehicle thus has better maneuverability with a small turning radius.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] The foregoing and further features and advantages of the invention will become apparent from the following description of example embodiments with reference to the accompanying drawings, wherein like numerals are used to represent like elements and wherein:

[0009] FIG. 1 is a schematic configuration diagram of a first embodiment of a four-wheel steering system that is mounted on a vehicle;

[0010] FIG. 2 is a control block diagram of a first ECU of the first embodiment;

[0011] FIG. 3 is a control block diagram of a second ECU of the first embodiment;

[0012] FIG. 4A is a plan view of a vehicle showing the phase relationship (antiphase) between front and rear wheels in the first embodiment;

[0013] FIG. 4B is a plan view of a vehicle showing the phase relationship (in phase) between front and rear wheels in the first embodiment;

[0014] FIG. 5 shows graphs A to C, where graph A shows the relationship between the steering angle and the steering torque in the first embodiment, graph B shows the relationship between the steering angle and the target steered angle of the rear wheels in the first embodiment, and graph C shows the relationship between the steering angle and the turning radius of a vehicle in the first embodiment;

[0015] FIG. 6 is a control block diagram of a target assist torque calculation circuit of the first embodiment;

[0016] FIG. 7 is a plan view showing turning characteristics of a vehicle in a comparative example;

[0017] FIG. 8 shows graphs A to C, where graph A shows the relationship between the steering angle and the steering torque in a second embodiment, graph B shows the relationship between the steering angle and the target steered angle of rear wheels in the second embodiment, and graph C shows the relationship between the steering angle and the turning radius of a vehicle in the second embodiment;

[0018] FIG. 9 is a flowchart of a process of switching steering control of the rear wheels in the second embodiment; and

[0019] FIG. 10 is a plan view showing turning characteristics of a vehicle in the second embodiment.

DETAILED DESCRIPTION OF EMBODIMENTS

[0020] A first embodiment of a four-wheel steering system of the invention will be described below. As shown in FIG. 1, a vehicle 10 is equipped with a four-wheel steering system 11. The four-wheel steering system 11 has a front-wheel steering system 13 that steers front wheels 12_{FR}, 12_{FL} and a rear-wheel steering system 14 that steers rear wheels 12_{RR}, 12_{RL}.

[0021] The front-wheel steering system 13 has a steering shaft 22 to which a steering wheel 21 is connected, a steered shaft 23 extending in the lateral direction of the vehicle 10 (the horizontal direction in FIG. 1), and a housing 24 accommodating the steered shaft 23 so that the steered shaft 23 can reciprocate therein. The steering shaft 22 is formed by a column shaft 25, an intermediate shaft 26, and a pinion shaft 27 which are connected together in this order from the steering wheel 21 side. The pinion shaft 27 crosses the steered shaft 23. Pinion teeth $27a$ of the pinion shaft 27 mesh with rack teeth $23a$ of the steered shaft 23. The right and left front wheels 12_{FR}, 12_{FL} are connected to respective ends of

the steered shaft **23** via tie rods **28** and knuckles, not shown. As the steering wheel **21** is turned, the steered shaft **23** moves linearly, whereby the steered angle θ_{wf} of the front wheels **12**$_{FR}$, **12**$_{FL}$ is changed.

[0022] The front-wheel steering system **13** has a motor **31**, a reduction gear mechanism **32**, and a pinion shaft **33** as a configuration that assists the driver in operating the steering wheel **21**. The motor **31** is a source of a steering assist force (assist force). A three-phase brushless motor is used as the motor **31**. A rotary shaft of the motor **31** is coupled to the pinion shaft **33** via the reduction gear mechanism **32**. Pinion teeth **33**a of the pinion shaft **33** mesh with rack teeth **23**b of the steered shaft **23**. Torque of the motor **31** is applied as a steering assist force to the steered shaft **23** via the pinion shaft **33**. The steered shaft **23** moves in the lateral direction of the vehicle **10** in accordance with rotation of the motor **31**.

[0023] The front-wheel steering system **13** has a first electronic control unit (ECU) **41**. The first ECU **41** controls the motor **31** based on the detection results of various sensors mounted on the vehicle **10**. The sensors include a vehicle speed sensor **42**, a torque sensor **43**, a steering angle sensor **44**, and a rotation angle sensor **45**. The vehicle speed sensor **42** detects the vehicle speed V. The torque sensor **43** is mounted on the column shaft **25**. The torque sensor **43** detects steering torque T_s applied to the steering shaft **22** via the steering wheel **21**. The steering angle sensor **44** is mounted between the steering wheel **21** and the torque sensor **43** on the column shaft **25**. The steering angle sensor **44** detects the steering angle θ_s, that is a rotation angle of the steering shaft **22**. The rotation angle sensor **45** is mounted on the motor **31**. The rotation angle sensor **45** detects the rotation angle θ_{mf} of the motor **31**. The first ECU **41** controls the motor **31** based on the vehicle speed V, the steering torque T_s the steering angle θ_s and the rotation angle θ_{mf} of the motor **31** which are detected by these sensors.

[0024] The rear-wheel steering system **14** has a steered shaft **51** extending in the lateral direction of the vehicle **10** (the horizontal direction in FIG. 1) and a housing **52** accommodating the steered shaft **51** so that the steered shaft **51** can reciprocate therein. The right and left rear wheels **12**$_{RR}$, **12**$_{RL}$ are connected to respective ends of the steered shaft **51** via tie rods **53** and knuckles, not shown. The rear-wheel steering system **14** has a motor **61**, a reduction gear mechanism **62**, and a pinion shaft **63** as a configuration that applies a steering force, namely power for steering the rear wheels **12**$_{RR}$, **12**$_{RL}$, to the steered shaft **51**. The motor **61** is a source of the steering force. A three-phase brushless motor is used as the motor **61**. A rotary shaft of the motor **61** is coupled to the pinion shaft **63** via the reduction gear mechanism **62**. Pinion teeth **63**a of the pinion shaft **63** mesh with rack teeth **51**a of the steered shaft **51**. Torque of the motor **61** is applied as a steering force to the steered shaft **51** via the pinion shaft **63**. The steered shaft **51** thus moves linearly in the lateral direction of the vehicle **10** with rotation of the motor **61**, whereby the steered angle θ_{wr} of the rear wheels **12**$_{RR}$, **12**$_{RL}$ is changed.

[0025] The rear-wheel steering system **14** has a second ECU **71**. The second ECU **71** controls the motor **61** based on the vehicle speed V, the steering angle θ_s, and the rotation angle θ_{mr} of the motor **61**. The rotation angle θ_{mr} of the motor **61** is detected by a rotation angle sensor **72** mounted on the motor **61**.

[0026] Next, the first ECU **41** will be described in detail. As shown in FIG. 2, the first ECU **41** includes a drive circuit **81** and a microcomputer **82**.

[0027] For example, a pulse width modulation (PWM)-controlled inverter circuit is used as the drive circuit **81**. The drive circuit **81** converts a direct current supplied from an on-board DC power supply such as a battery to a three-phase alternating current, based on a drive signal (PWM signal) S_{cf} generated by the microcomputer **82**. This three-phase alternating current is supplied to the motor **31** through a power supply path **83**. A current sensor **84** is disposed on the power supply path **83**. The current sensor **84** detects an actual current value I_{mf} on the power supply path **83**.

[0028] The microcomputer **82** has various arithmetic circuits that are implemented by executing a control program stored in a storage device, not shown, of the first ECU **41**. The microcomputer **82** includes, as the arithmetic circuits, a target assist torque calculation circuit **85**, a current command value calculation circuit **86**, and a drive signal generation circuit **87**.

[0029] The target assist torque calculation circuit **85** calculates target assist torque T_{as}^* based on the steering torque T_s and the vehicle speed V. The target assist torque T_{as}^* is a target value of a rotational force (torque) to be generated by the motor **31**. The target assist torque calculation circuit **85** sets the absolute value of the target assist torque T_{as}^* to a larger value as the absolute value of the steering torque T_s increases and the vehicle speed V decreases.

[0030] The current command value calculation circuit **86** calculates a current command value I* based on the target assist torque T_{as}^* calculated by the target assist torque calculation circuit **85**. For example, the current command value calculation circuit **86** calculates the current command value I* by dividing the target assist torque T_{as}^* by a torque constant of the motor **31**. The current command value I* is a target value of a current to be supplied to the motor **31** in order to cause the motor **31** to generate the target assist torque T_{as}^*.

[0031] The drive signal generation circuit **87** performs current feedback control in accordance with the rotation angle θ_{mf} of the motor **31** so that the actual current value I_{mf} that is supplied to the motor **31** follows the current command value I*. The drive signal generation circuit **87** calculates the deviation between the current command value I* and the actual current value I_{mf} and generates a drive signal S_{cf} for the drive circuit **81** so as to eliminate the deviation. A current in accordance with the drive signal S_{cf} is supplied to the motor **31** through the drive circuit **81**, whereby the motor **31** generates a rotational force in accordance with the target assist torque T_{as}^*.

[0032] The second ECU **71** will be described in detail. As shown in FIG. 3, the second ECU **71** includes a drive circuit **91** and a microcomputer **92**.

[0033] A PWM-controlled inverter circuit is used also as the drive circuit **91**. The drive circuit **91** converts a direct current supplied from an on-board DC power supply such as a battery to a three-phase alternating current, based on a drive signal (PWM signal) S_{cr} generated by the microcomputer **92**.

[0034] The microcomputer **92** has various arithmetic circuits that are implemented by executing a control program stored in a storage device, not shown, of the second ECU **71**. The microcomputer **92** includes, as the arithmetic circuits, a

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steered angle calculation circuit **93**, a target steered angle calculation circuit **94**, and a drive signal generation circuit **95**.

[0035] The steered angle calculation circuit **93** calculates an actual steered angle θ_{wr} of the rear wheels 12_{RR}, 12_{RL} based on the rotation angle θ_{mr} of the motor **61** which is detected by the rotation angle sensor **72**. The motor **61** is coupled to the pinion shaft **63** via the reduction gear mechanism **62**. The pinion teeth **63***a* of the pinion shaft **63** mesh with the rack teeth **51***a* of the steered shaft **51**. Accordingly, there is a correlation between the rotation angle θ_{mr} of the motor **61** and the rotation angle of the pinion shaft **63** and thus between the rotation angle θ_{mr} of the motor **61** and the displacement of the steered shaft **51**. The steered angle calculation circuit **93** can calculate the steered angle θ_{wr} of the rear wheels 12_{RR}, 12_{RL} from the rotation angle θ_{mr} of the motor **61** by using this correlation.

[0036] The target steered angle calculation circuit **94** calculates a target steered angle θ_{wr}* of the rear wheels 12_{RR}, 12_{RL} based on the steering angle θ_s and the vehicle speed V. The target steered angle calculation circuit **94** calculates the target steered angle θ_{wr}* of the rear wheels 12_{RR}, 12_{RL} by using steering characteristics maps that define the relationship between the steering angle θ_s and the target steered angle θ_{wr}*. The target steered angle calculation circuit **94** uses the steering characteristics maps with different characteristics between the case where the vehicle speed V is in a low speed range lower than a vehicle speed threshold (e.g., 30 km/h) and the case where the vehicle speed V is in a medium to high speed range equal to or higher than the vehicle speed threshold. The steering characteristics maps are stored in the storage device of the second ECU **71**.

[0037] When the vehicle speed V is in the low speed range lower than the vehicle speed threshold, the target steered angle calculation circuit **94** calculates the target steered angle θ_{wr}* of the rear wheels 12_{RR}, 12_{RL} so that the rear wheels 12_{RR}, 12_{RL} are steered in the opposite direction (antiphase) to that in which the front wheels 12_{FR}, 12_{FL} are steered. As shown in FIG. **4A**, since the steered angle θ_{wr} of the rear wheels 12_{RR}, 12_{RL} is in antiphase with the steered angle O_{wf} of the front wheels 12_{FR}, 12_{FL}, the overall turning radius R1 of the vehicle **10** is smaller than the turning radius R2 in the case where the vehicle **10** is a two-wheel steering vehicle (in the case where the direction in which the rear wheels 12_{RR}, 12_{RL} are steered is kept in such a direction that the vehicle **10** moves straight). The vehicle **10** therefore has improved maneuverability with a small turning radius.

[0038] When the vehicle speed V is in the medium to high speed range equal to or higher than the vehicle speed threshold, the target steered angle calculation circuit **94** calculates the target steering angle θ_{wr}* of the rear wheels 12_{RR}, 12_{RL} so that the rear wheels 12_{RR}, 12_{RL} are steered in the same direction (in phase) as that in which the front wheels 12_{FR}, 12_{FL} are steered. Since the steered angle θ_{wr} of the rear wheels 12_{RR}, 12_{RL} is in phase with the steered angle θ_{wf} of the front wheels 12_{FR}, 12_{FL} as shown in FIG. **4B**, this provides driving stability when making lane changes or turning corners. In the case where the steered angle θ_{wr} of the rear wheels 12_{RR}, 12_{RL} is set to the same angle as the steered angle θ_{wf} of the front wheels 12_{FR}, 12_{FL}, this allows the vehicle **10** to move obliquely, parallel to the direction in which the rear wheels 12_{RR}, 12_{RL} and the front wheels 12_{FR}, 12_{FL} are steered.

[0039] The drive signal generation circuit **95** performs feedback control of the steered angle θ_{wr} in accordance with the rotation angle θ_{mr} of the motor **31** so that the actual steered angle θ_{wr} of the rear wheels 12_{RR}, 12_{RL} follows the target steered angle θ_{wr}*. The drive signal generation circuit **95** calculates the deviation between the target steered angle θ_{wr}* and the actual steered angle θ_{wr} and generates a drive signal S_{cr} for the drive circuit **91** so as to eliminate the deviation. A current in accordance with the drive signal S_{cr} is supplied to the motor **61** through the drive circuit **91**, whereby the motor **61** operates so as to eliminate the deviation between the target steered angle θ_{wr}* and the actual steered angle θ_{wr}.

[0040] The steering characteristics map that is used by the target steered angle calculation circuit **94** when the vehicle speed V is in the low speed range will be described.

[0041] In this example, the steering angle θ_s is processed as a positive value in the case where the steering wheel **21** has been turned to the left with respect to its neutral position and is processed as a negative value in the case where the steering wheel **21** has been turned to the right with respect to its neutral position. The steering torque T_s detected by the torque sensor **43** is processed as a positive value in the case where the steering wheel **21** has been turned to the left with respect to its neutral position and is processed as a negative value in the case where the steering wheel **21** has been turned to the right with respect to its neutral position.

[0042] As shown in graph B of FIG. **5**, a steering characteristics map M1 is a map with the abscissa representing the steering angle θ_s and the ordinate representing the target steered angle θ_{wr}* of the rear wheels 12_{RR}, 12_{RL} and defines the relationship between the steering angle θ_s and the target steered angle θ_{wr}*. The steering characteristics map M1 has the following characteristics.

[0043] When the steering angle θ_s is 0 (zero) that corresponds to the state where the vehicle **10** is moving straight (the steering wheel **21** is located at its neutral position), the target steered angle θ_{wr}* is 0 (zero). When the absolute value of the steering angle θ_s is smaller than the absolute value of angle thresholds θ_{th}, $-\theta_{th}$, the absolute value of the target steered angle θ_{wr}* gradually increases linearly with an increase in absolute value of the steering angle θ_s. When the absolute value of the steering angle θ_s is equal to or larger than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$, the absolute value of the target steered angle θ_{wr}* sharply increases linearly with respect to an increase in absolute value of the steering angle θ_s. That is, the rate of increase in absolute value of the target steered angle θ_{wr}* with respect to an increase in absolute value of the steering angel θ_s (the slope of the characteristics line) is higher (steeper) when the absolute value of the steering angle θ_s is equal to or larger than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$ than when the absolute value of the steering angle θ_s is smaller than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$. In other words, the gradient of increase in absolute value of the target steered angle θ_{wr}* with respect to an increase in absolute value of the steering angle θ_s is steeper when the absolute value of the steering angle θ_s is equal to or larger than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$ than when the absolute value of the steering angle θ_s is smaller than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$.

[0044] The positive and negative angle thresholds θ_{th}, $-\theta_{th}$ are set to values near limit steering angles θ_{max}, $-\theta_{max}$ at which the steering wheel **21** reaches a limit position in its

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physical operation range. However, the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$ is smaller than the absolute value of the limit steering angles θ_{max}, $-\theta_{max}$. For example, the limit steering angles θ_{max}, $-\theta_{max}$ of the steering wheel **21** are determined by either the upper limit of the steering angle θ_s which is determined by the length of a spiral cable disposed in the steering wheel **21** or the steering angle θ_s at which the steered shaft **23** reaches a limit position in its physical movable range (the position where an end of the steered shaft **23** contacts the housing **24**).

[0045] By setting the target steered angle $\theta_{wr}{}^*$ of the rear wheels 12_{RR}, 12_{RL} in accordance with the steering characteristics map M1, the turning radius of the vehicle **10** changes with a change in steering angle θ_s in the following manner. As shown in graph C of FIG. **5**, when the absolute value of the steering angle θ_s is smaller than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$, the absolute value of the turning radius R gradually decreases with respect to an increase in absolute value of the steering angle θ_s. When the absolute value of the steering angle θ_s is equal to or larger than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$, the absolute value of the turning radius R sharply decreases with an increase in steering angle θ_s. That is, the rate of decrease in absolute value of the turning radius R with respect to an increase in absolute value of the steering angle θ_s (the slope of the characteristics line) is higher (steeper) when the absolute value of the steering angle θ_s is equal to or larger than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$ than when the absolute value of the steering angle θ_s is smaller than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$. In other words, the gradient of decrease in absolute value of the turning radius R with respect to an increase in absolute value of the steering angle θ_s is steeper when the absolute value of the steering angle θ_s is equal to or larger than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$ than when the absolute value of the steering angle θ_s is smaller than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$.

[0046] The larger the absolute value of the steering angle θ_s is, the stronger the driver's intention to turn the vehicle **10** with a smaller turning radius is. Especially when the absolute value of the steering angle θ_s is larger than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$ that are near the limit steering angles θ_{max}, $-\theta_{max}$, it is assumed that the driver is trying to make a sharp turn. In the present embodiment, when the absolute value of the steering angle θ_s is equal to or larger than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$, the rate of increase in absolute value of the target steered angle $\theta_{wr}{}^*$ of the rear wheels 12_{RR}, 12_{RL} with respect to an increase in absolute value of the steering angel θ_s is increased sharply, so that the absolute value of the turning radius R of the vehicle **10** sharply decreases with respect to an increase in absolute value of the steering angle θ_s.

[0047] That is, since the vehicle **10**'s maneuverability with a small turning radius is rapidly improved, the vehicle **10** can easily respond to the driver's intention to make a sharp turn. Since the absolute value of the target steered angle $\theta_{wr}{}^*$ of the rear wheels 12_{RR}, 12_{RL} is increased sharply with respect to an increase in absolute value of the steering angle θ_s, this facilitates driver's maneuver to turn the vehicle **10**. The vehicle **10** can thus respond to the driver's request to turn the vehicle **10** with as small a turning radius as possible.

[0048] However, when the absolute value of the steering angle θ_s is equal to or larger than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$, the absolute value of the turning

radius R of the vehicle **10** sharply decreases with respect to an increase in absolute value of the steering angle θ_s. The driver may therefore get an uncomfortable driving feel. Accordingly, in the present embodiment, the driver is notified of a rapid change in steering characteristics of the rear wheels 12_{RR}, 12_{RL} by a change in steering torque T_s. An example of characteristics of the steering torque T_s is as follows.

[0049] As shown in graph A of FIG. **5**, when the absolute value of the steering angle θ_s is smaller than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$, the absolute value of the steering torque T_s gradually increases with an increase in absolute value of the steering angle θ_s. When the absolute value of the steering angle θ_s is equal to or larger than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$, the absolute value of the steering torque T_s sharply increases with respect to an increase in absolute value of the steering angle θ_s. That is, the rate (gradient) of increase in absolute value of the steering torque T_s with respect to an increase in absolute value of the steering angel θ_s is higher (steeper) when the absolute value of the steering angle θ_s is equal to or larger than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$ than when the absolute value of the steering angle $_e$, is smaller than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$.

[0050] The characteristics of the steering torque T_s shown by graph A of FIG. **5** are implemented by controlling the target assist torque $T_{as}{}^*$ by the target assist torque calculation circuit **85**. A specific example is as follows.

[0051] As shown in FIG. **6**, the target assist torque calculation circuit **85** has a base assist torque calculation circuit **85**a, a correction amount calculation circuit **85**b, and a subtractor **85**c.

[0052] The base assist torque calculation circuit **85**a calculates base assist torque T_{as} by using a three-dimensional map that defines the relationship between the steering torque T_s and the base assist torque T_{as} in accordance with the vehicle speed V. The base assist torque calculation circuit **85**a sets the absolute value of the base assist torque T_{as} to a larger value as the absolute value of the steering torque T_s increases and the vehicle speed V decreases. The base assist torque T_{as} is a basic component of the target assist torque $T_{as}{}^*$.

[0053] The correction amount calculation circuit **85**b calculates the amount of correction T_c for the base assist torque T_{as} by using a correction map that defines the relationship between the steering angle θ_s and the amount of correction T_c. The correction map has characteristics in accordance with the characteristics of the steering torque T_s shown in graph A of FIG. **5**. When the absolute value of the steering angle θ_s is equal to or larger than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$, the absolute value of the amount of correction T_c sharply increases with respect to an increase in absolute value of the steering angle θ_s.

[0054] The subtractor **85**c calculates the target assist torque $T_{as}{}^*$ by subtracting the amount of correction T_c from the base assist torque T_{as}. The target assist torque $T_{as}{}^*$ and thus the steering assist force that is generated by the motor **31** therefore decrease in accordance with the amount of correction T_c. Accordingly, when the absolute value of the steering angle θ_s is equal to or larger than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$, the absolute value of the steering assist force sharply decreases with respect to an increase in absolute value of the steering angle θ_s, and the

absolute value of the steering torque T_s therefore sharply increases with respect to an increase in absolute value of the steering angle θ_s.

[0055] When the driver feels such a sharp increase in absolute value of the steering torque T_s he or she can recognize that the steering characteristics of the rear wheels 12_{RR}, 12_{RL} will change rapidly if he or she turns the steering wheel 21 any further in such a direction that the absolute value of the steering angle θ_s increases, namely can recognize that the turning radius R of the vehicle 10 will sharply decrease with respect to an increase in absolute value of the steering angle θ_s. Accordingly, when, e.g., making a sharp turn, the driver turns the steering wheel 21 after he or she recognizes that the steering characteristics of the rear wheels 12_{RR}, 12_{RL} will change rapidly. This restrains the driver from getting an uncomfortable driving feel or feeling an uncomfortable vehicle behavior.

[0056] The first embodiment has the following effects.

[0057] (1) While the vehicle 10 is moving in the low speed range, the absolute value of the target steered angle $\theta_{wr}*$ of the rear wheels 12_{RR}, 12_{RL} sharply increases with respect to an increase in absolute value of the steering angle θ_s when the absolute value of the steering angle θ_s is equal to or larger than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$. The vehicle 10 therefore has improved maneuverability with a small turning radius.

[0058] (2) When the absolute value of the steering angle θ_s is equal to or larger than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$, the absolute value of the steering torque T_s sharply increases with respect to an increase in absolute value of the steering angle θ_s. The driver therefore can feel through the steering wheel 21 a sharp increase in steered angle θ_{wr} of the rear wheels 12_{RR}, 12_{RL} with respect to an increase in steering angle θ_s. Since the driver can thus be prepared for a sharp decrease in turning radius R of the vehicle 10 with respect to an increase in steering angle O he or she is less likely to get an uncomfortable driving feel.

[0059] (3) The angle thresholds θ_{th}, $-\theta_{th}$ are set to values near the limit steering angles θ_{max}, $-\theta_{max}$ at which the steering wheel 21 reaches the limit position in its physical operation range. When the steering wheel 21 is turned to a position near the limit position in its physical operation range, it is assumed that the driver wants to turn the vehicle 10 with as small a turning radius R as possible. In such a situation, it is preferable to reduce the turning radius R of the vehicle 10 as much as possible.

[0060] Next, a second embodiment of the four-wheel steering system will be described. The four-wheel steering system of the present embodiment basically has a configuration similar to that of the first embodiment shown in FIGS. 1 to 3.

[0061] As shown in FIG. 7, in the case where the vehicle 10 is a four-wheel steering vehicle, the rear wheels 12_{RR}, 12_{RL} are steered in the opposite direction to that in which the front wheels 12_{FR}, 12_{FL} are steered, when the vehicle 10 turns. In this case, the overall turning radius R1 of the vehicle 10 is smaller than the turning radius R2 in the case where the vehicle 10 is a two-wheel steering vehicle. However, the rear part of the vehicle 10 moves more outward of the turn in the early stage of the turn as compared to the case where the vehicle 10 is a two-wheel steering vehicle.

[0062] That is, in the case where the vehicle 10 is a two-wheel steering vehicle in which the direction in which the rear wheels 12_{RR}, 12_{RL} are steered is kept in such a direction that the vehicle 10 moves straight, the vehicle 10 turns about the turning center C2 of the two-wheel steering vehicle with a corner Pc of the rear end of the vehicle 10 (e.g., a corner of a rear bumper) moving along a path substantially in the direction in which the rear wheels 12_{RR}, 12_{RL} are steered, as shown by dashed arrow A2 in FIG. 7. The corner Pc of the rear end of the vehicle 10 therefore does not move outward of the turn with respect to an outer side surface of the vehicle 10 which is an outer side surface in the case where the vehicle 10 moves straight.

[0063] However, in the case where the vehicle 10 is a four-wheel steering vehicle, the vehicle 10 turns about the turning center C1 of the four-wheel steering vehicle with the corner Pc of the rear end of the vehicle 10 moving along a path substantially in the direction in which the rear wheels 12_{RR}, 12_{RL} are steered, namely in the direction in antiphase with that in which the front wheels 12_{FR}, 12_{FL} are steered, as shown by continuous arrow A1 in FIG. 7. In the early stage of the turn, the corner Pc of the rear end of the vehicle 10 therefore moves outward of the turn with respect to an outer side surface of the vehicle 10 which is an outer side surface in the case where the vehicle 10 moves straight.

[0064] Accordingly, when the vehicle 10 parked along an obstacle Wo such as a wall starts to move, the rear part of the vehicle 10 moves outward of a turn in the early stage of the turn. There is therefore a risk that the corner Pc of the rear end of the vehicle 10 may contact the obstacle Wo. The larger the steered angle θ_{wr} of the rear wheels 12_R, 12_{RL} is, the more this is likely to occur. This is because the larger the steered angle θ_{wr} of the rear wheels 12_{RR}, 12_{RL} is, the smaller the turning radius of the vehicle 10 is and the more the rear part of the vehicle 10 moves outward of the turn.

[0065] The four-wheel steering system of the present embodiment has the following configuration.

[0066] As shown in FIG. 10, the vehicle 10 is equipped with obstacle sensors 10R, 10L at two corners Pc, namely right and left corners Pc, of the rear end thereof. The obstacle sensors 10R, 10L detect in a non-contact manner the corners Pc of the vehicle 10 approaching the obstacle Wo such as a wall.

[0067] The storage device of the second ECU 71 stores therein a steering characteristics map M2 shown in graph B of FIG. 8 in addition to the steering characteristics map M1. The second ECU 71 switches the steering characteristics map to be used to calculate the target steered angle $\theta_{wr}*$ of the rear wheels 12_{RR}, 12_m, between the steering characteristics map M1 and the steering characteristics map M2 based on the detection results of the obstacle sensors 10R, 10L. For example, the steering characteristics map M2 has first characteristics shown by a continuous line in graph B of FIG. 8 or second characteristics shown by a long dashed double-short dashed line in graph B of FIG. 8, in accordance with the product specifications etc.

[0068] The first characteristics of the steering characteristics map M2 are as follows.

[0069] As shown by the continuous line in graph B of FIG. 8, when the absolute value of the steering angle θ_s is smaller than the absolute value of the positive and negative angle thresholds θ_{th}, $-\theta_{th}$, the absolute value of the target steered angle $\theta_{wr}*$ gradually increases linearly with an increase in absolute value of the steering angle θ_s. When the absolute value of the steering angle θ_s is equal to or larger than the absolute value of the positive and negative angle thresholds θ_{th}, $-\theta_{th}$, the absolute value of the target steered angle $\theta_{wr}*$

is kept constant regardless of the absolute value of the steering angle θ_s. The characteristics of the steering characteristics map M2 are different from those of the steering characteristics map M1 in this respect.

[0070] By setting the target steered angle θ_{wr}^* of the rear wheels 12_{RR}, 12_{RL} in accordance with the steering characteristics map M2, the turning radius R of the vehicle 10 changes with a change in steering angle θ_s in the following manner.

[0071] As shown by continuous lines in graph C of FIG. 8, when the absolute value of the steering angle θ_s is smaller than the absolute value of the angle thresholds θ_{th}-θ_{th}, the absolute value of the turning radius R gradually decreases with an increase in absolute value of the steering angle θ_s. When the absolute value of the steering angle θ_s is equal to or larger than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$, the absolute value of the turning radius R is kept constant regardless of the steering angle θ_s. Unlike in the steering characteristics map M1, when the absolute value of the steering angle θ_s is equal to or larger than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$, the absolute value of the turning radius R does not rapidly decrease with respect to an increase in absolute value of the steering angle θ_s.

[0072] As described above, in the case where the target steered angle θ_{wr}^* of the rear wheels 12_{RR}, 12_{RL} is calculated by using the steering characteristics map M2, the steering characteristics of the rear wheels 12_{RR}, 12_{RL} do not rapidly change. It is therefore not necessary to rapidly change the steering torque T_s in order to notify the driver of a rapid change in steering characteristics. Accordingly, the steering torque T_s is controlled in the following manner in the case where the target steered angle θ_{wr}^* of the rear wheels 12_{RR}, 12_{RL} is calculated by using the steering characteristics map M2.

[0073] As shown in graph A of FIG. 8, the absolute value of the steering torque T_s gradually increases linearly with an increase in absolute value of the steering angle θ_s in the entire operation range of the steering wheel 21 ($0 \le |\theta_s| \le |\pm\theta_{max}|$).

[0074] The second characteristics of the steering characteristics map M2 are as follows.

[0075] As shown by the long dashed double-short dashed line in graph B of FIG. 8, the absolute value of the target steered angle θ_{wr}^* is kept at 0 (zero) regardless of the value of the steering angle θ_s. In the case where the steering characteristics map M2 with the second characteristics is used, the rear wheels 12_{RR}, 12_{RL} are kept at a steering neutral position, namely the position corresponding to the state where the vehicle 10 is moving straight, regardless of the steering angle θ_s, as in the case of a normal two-wheel steering vehicle. In the case where the steering characteristics map M2 with the second characteristics is used, the turning radius R of the vehicle 10 is kept constant in accordance with the steered angle θ_{wf} of the front wheels 12_{FR}, 12_{FL}, as shown by long dashed double-short dashed lines in graph C of FIG. 8. The steering torque T_s is controlled in a manner similar to that of the steering characteristics map M2 with the first characteristics shown in graph A of FIG. 8.

[0076] A process of switching steering control of the rear wheels 12_{RR}, 12_{RL} by the second ECU 71 will be described. It is herein assumed that the vehicle speed V is in the low speed range lower than the vehicle speed threshold (e.g., 30 km/h).

[0077] As shown by the flowchart of FIG. 9, the second ECU 71 determines if any obstacle Wo has been detected by at least one of the obstacle sensors 10R, 10L (step S101). If it is determined that no obstacle Wo has been detected by at least one of the obstacle sensors 10R, 10L (NO in step S101), the second ECU 71 performs steering control of the rear wheels 12_{RR}, 12_{RL} by using the steering characteristics map M1 (step S102). If it is determined that an obstacle Wo has been detected by at least one of the obstacle sensors 10R, 10L (YES in step S101), the second ECU 71 performs steering control of the rear wheels 12_{RR}, 12_{RL} by using the steering characteristics map M2 (step S102).

[0078] The second embodiment has the following functions and effects.

[0079] It is herein assumed that the vehicle 10 parked along an obstacle Wo such as a wall starts to move with the rear wheels 12_{RR}, 12_{RL} steered in antiphase with the front wheels 12_{FR}, 12_{FL} as shown by continuous lines in FIG. 10. In this case, as shown by dashed lines in FIG. 10, the corner Pc (in this example, the left corner Pc) of the rear part of the vehicle 10 approaches the obstacle Wo as the vehicle 10 turns. When at least one of the obstacle sensors 10R, 10L detects the corner Pc approaching the obstacle Wo, the steering control of the rear wheels 12_{RR}, 12_{RL} is switched from the steering control using the steering characteristics map M1 to the steering control using the steering characteristics map M2.

[0080] In the case where the steering characteristics map M2 has the second characteristics (the steered angle θ_{wr} of the rear wheels 12_{RR}, 12_{RL} is always set to 0), the rear wheels 12_{RR}, 12_{RL} are turned to the steering neutral position. As a result, the turning center of the vehicle 10 moves from the turning center C1 for four-wheel steering to the turning center C2 for two-wheel steering. Thereafter, as shown by long dashed short dashed lines in FIG. 10, the corner Pc of the rear part of the vehicle 10 does not move outward of the turn anymore and the vehicle 10 can turn so as to move away from the obstacle Wo as a normal two-wheel steering vehicle does. The corner Pc of the rear part of the vehicle 10 is thus restrained from contacting the obstacle Wo.

[0081] In the case where the steering characteristics map M2 has the first characteristics, namely in the case where the absolute value of the target steered angle θ_{wr}^* of the rear wheels 12_{RR}, 12_{RL} gradually increases with respect to an increase in absolute value of the steering angle θ_s, the absolute value of the steered angle θ_{wr} of the rear wheels 12_{RR}, 12_{RL} does not sharply increase with respect to an increase in absolute value of the steering angle θ_s even when the absolute value of the steering angle θ_s is equal to or larger than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$. The corner Pc of the rear part of the vehicle 10 is thus restrained from contacting the obstacle Wo.

[0082] The first and second embodiments may be modified as follows.

[0083] In the first and second embodiments, the first ECU 41 and the second ECU 71 detect the steering angle θ_s via the steering angle sensor 44. However, the steering angle θ_s may be calculated based on the rotation angle θ_{mf} of the motor 31 which is detected by the rotation angle sensor 45. The motor 31 is coupled to the steering shaft 22 via the reduction gear mechanism 32, the pinion shaft 33, and the steered shaft 23. Accordingly, there is a correlation between the rotation angle θ_{mf} of the motor 31 and the steering angle θ_s. The steering angle θ_s can therefore be calculated from the

rotation angle θ_{mf} of the motor **31**. With this configuration, the invention can also be suitably applied to a vehicle **10** that is not equipped with the steering angle sensor **44**, depending on the specifications of the vehicle **10** etc.

[0084] In the first and second embodiments, the front-wheel steering system **13** is configured to apply torque of the motor **31** to the steered shaft **23**. However, for example, the front-wheel steering system **13** may be configured to apply torque of the motor **31** to the steering shaft **22** (the column shaft **25**).

[0085] In the first embodiment, the front-wheel steering system **13** is configured to assist in steering by applying torque of the motor **31** to the steered shaft **23**. However, the configuration that assists in steering may be omitted depending on the specifications of the vehicle **10** etc. In this case, the front wheels $\mathbf{12}_{FR}$, $\mathbf{12}_{FL}$ are steered only by the driver's steering operation.

[0086] In the second embodiment, in the case where at least one of the obstacle sensors **10R**, **10L** detects the corner Pc of the rear part of the vehicle **10** approaching an obstacle Wo, the rear wheels $\mathbf{12}_{RR}$, $\mathbf{12}_{RL}$ may be steered in the same direction as that in which the front wheels $\mathbf{12}_{FR}$, $\mathbf{12}_{FL}$ are steered when the absolute value of the steering angle θ_s is equal to or larger than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$. This allows the vehicle **10** to move parallel to the direction in which the front wheels $\mathbf{12}_{FR}$, $\mathbf{12}_{FL}$ and the rear wheels $\mathbf{12}_{RR}$, $\mathbf{12}_{RL}$ are steered so as to move away from the obstacle Wo, although it depends on the steered angle θ_{wr} of the rear wheels $\mathbf{12}_{RR}$, $\mathbf{12}_{RL}$. The corner Pc of the rear part of the vehicle **10** is thus restrained from contacting the obstacle Wo.

[0087] In the first and second embodiments, the relationship between the steering angle θ_s and the rotation radius (turning radius R) of the vehicle may be defined so that, when the absolute value of the steering angle θ_s is in the range from zero to the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$, the rotation radius of the vehicle is in a commonly used range that is required for normal steering operation, and when the absolute value of the steering angle θ_s is in the range larger than the absolute value of the angle thresholds θ_{th}-θ_{th}, the rotation radius of the vehicle is in a non-commonly used range that is not required for normal steering operation. In this case, when the absolute value of the steering angle θ_s is in the range from zero to the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$ which is the switch point of the steering characteristics, control is performed mainly so as to provide the driver and occupants with a natural feel (driving feel, riding feel, etc.). When the absolute value of the steering angle θ_s is in the range larger than the absolute value of the angle thresholds θ_{th}, $-\theta_{th}$, control is performed mainly so as to provide good maneuverability with a small turning radius. However, since this range corresponds to the non-commonly used range, the impact of such control on the driver or occupants is not significant.

What is claimed is:

1. A four-wheel steering system, comprising:
   a front-wheel steering system that steers front wheels of a vehicle; and
   a rear-wheel steering system that steers rear wheels of the vehicle in accordance with a steering angle that is a rotation angle of a steering wheel, wherein,

   when a vehicle speed is lower than a vehicle speed threshold, the rear-wheel steering system steers the rear wheels in an opposite direction to that in which the front wheels are steered, and

   when the vehicle speed is lower than the vehicle speed threshold, the rear-wheel steering system sharply increases a rate of increase in steered angle of the rear wheels with respect to an increase in steering angle when an absolute value of the steering angle is equal to or larger than an absolute value of an angle threshold.

2. The four-wheel steering system according to claim **1**, wherein,
   the front-wheel steering system has a motor that is a source of a steering assist force and a control device that controls the motor in accordance with a steering state, and

   when the vehicle speed is lower than the vehicle speed threshold, the control device controls the motor so as to sharply increase a rate of increase in steering torque with respect to an increase in steering angle when the absolute value of the steering angle is equal to or larger than the absolute value of the angle threshold.

3. The four-wheel steering system according to claim **1**, wherein,
   when an obstacle sensor mounted on a rear part of the vehicle detects a corner of the rear part of the vehicle approaching an obstacle, the rear-wheel steering system does not perform such control that sharply increases the rate of increase in steered angle of the rear wheels with respect to an increase in steering angle even when the absolute value of the steering angle is equal to or larger than the absolute value of the angle threshold.

4. The four-wheel steering system according to claim **1**, wherein,
   the angle threshold is set to a value near a limit steering angle at which the steering wheel reaches a limit position in its physical operation range.

5. A four-wheel steering system, comprising:
   a front-wheel steering system that steers front wheels of a vehicle; and
   a rear-wheel steering system that steers rear wheels of the vehicle in accordance with a steering angle that is a rotation angle of a steering wheel, wherein,

   when a vehicle speed is lower than a vehicle speed threshold, the rear-wheel steering system steers the rear wheels in an opposite direction to that in which the front wheels are steered, and

   when an obstacle sensor mounted on a rear part of the vehicle detects a corner of the rear part of the vehicle approaching an obstacle, the rear-wheel steering system either returns the rear wheels to a steering neutral position corresponding to a state where the vehicle is moving straight or steers the rear wheels in the same direction as that in which the front wheels are steered, when an absolute value of the steering angle is equal to or larger than an absolute value of an angle threshold.

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