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(54) **TURNING CONTROL DEVICE**

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(57) **ABSTRACT**

A turning control device includes a processor. The processor is configured to execute a turning-corresponding angle acquisition process, a rudder angle variable estimation process, a basic assist torque setting process, an adjusting torque calculation process, and a manipulation process. The basic assist torque setting process is a process of setting the value of a basic assist torque variable depending on a steering torque. The adjusting torque calculation process is a process of calculating the value of an adjusting torque variable. The manipulation process includes a process of manipulating a drive circuit of an assist motor, so as to control the torque of the assist motor to a torque depending on the sum of a torque indicated by the value of the basic assist torque variable and a torque indicated by the value of the adjusting torque variable.

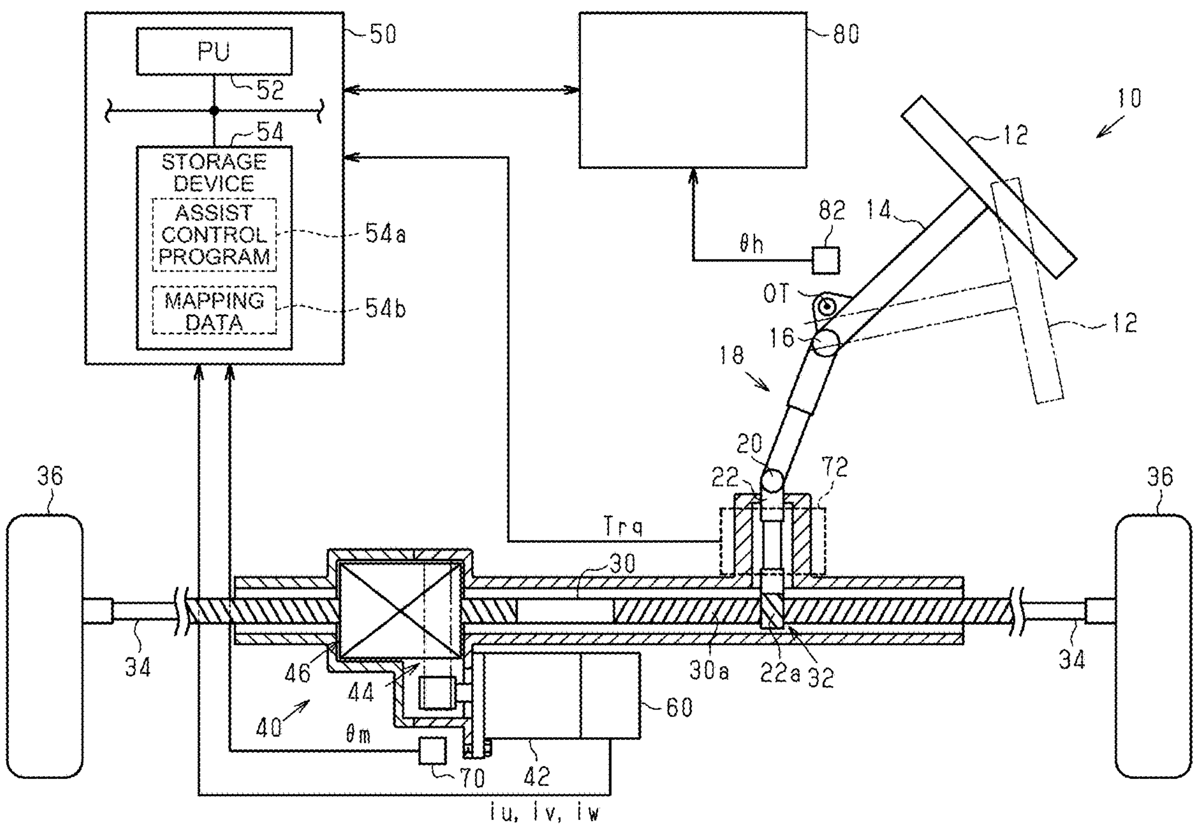


FIG. 1

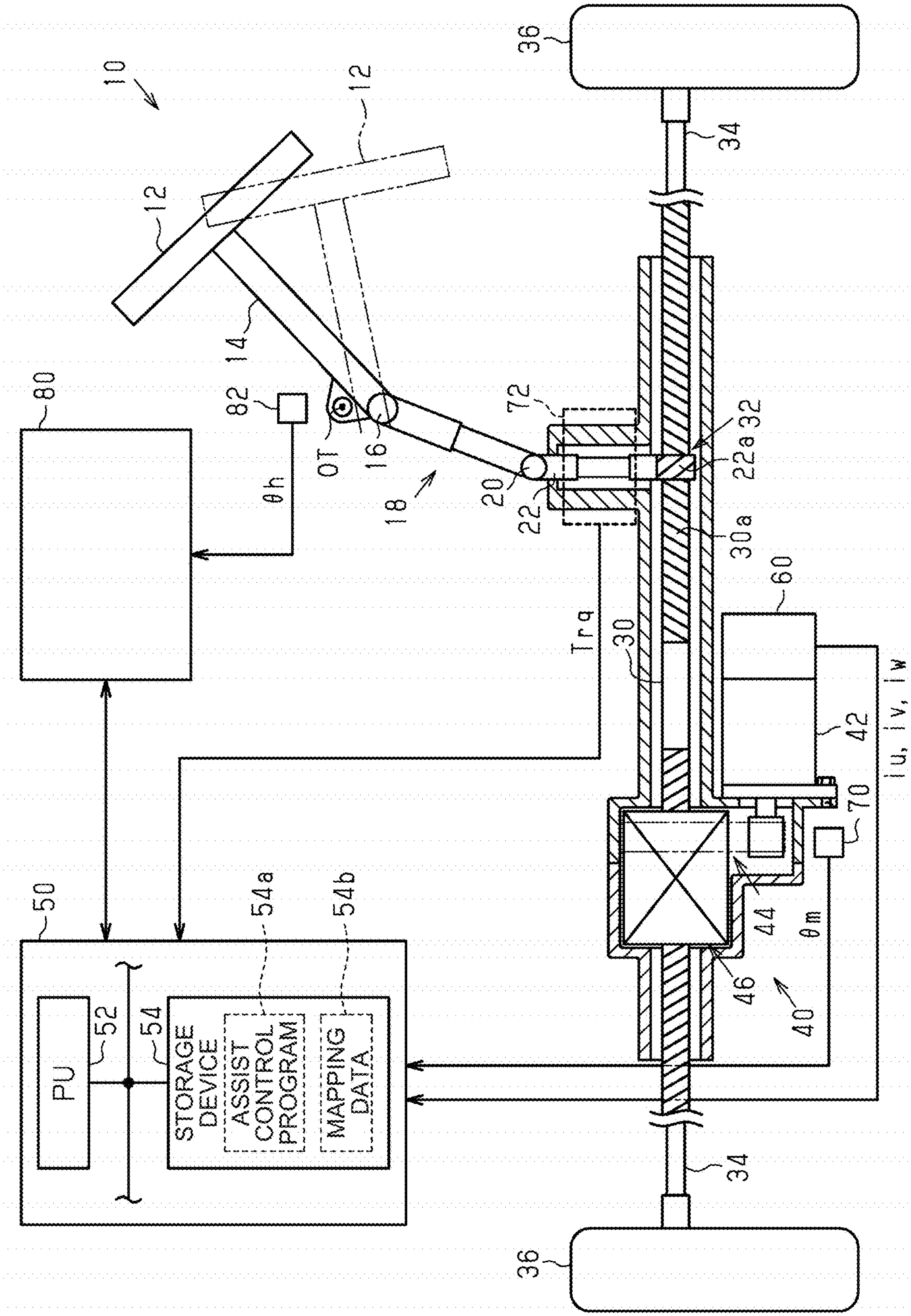

10
12
12
14
16
OT
18
20
22
22a
32
72
30a
30
Trq
θh
82
80
60
42
Iu, Iv, Iw
70
44
θm
46
40
34
34
36
36
50
54a
54b
52
54
PU
STORAGE DEVICE
ASSIST CONTROL PROGRAM
MAPPING DATA

FIG. 2

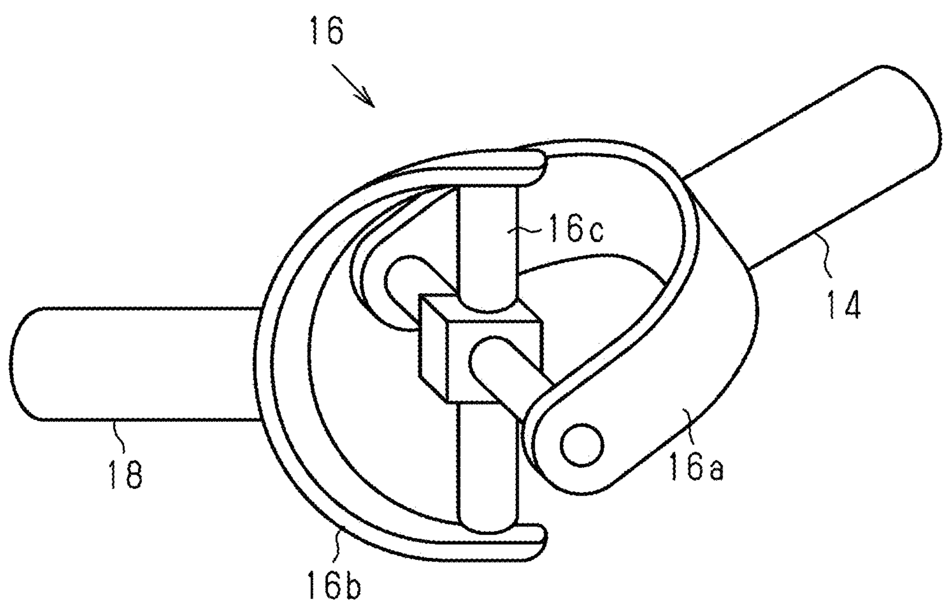


FIG. 3

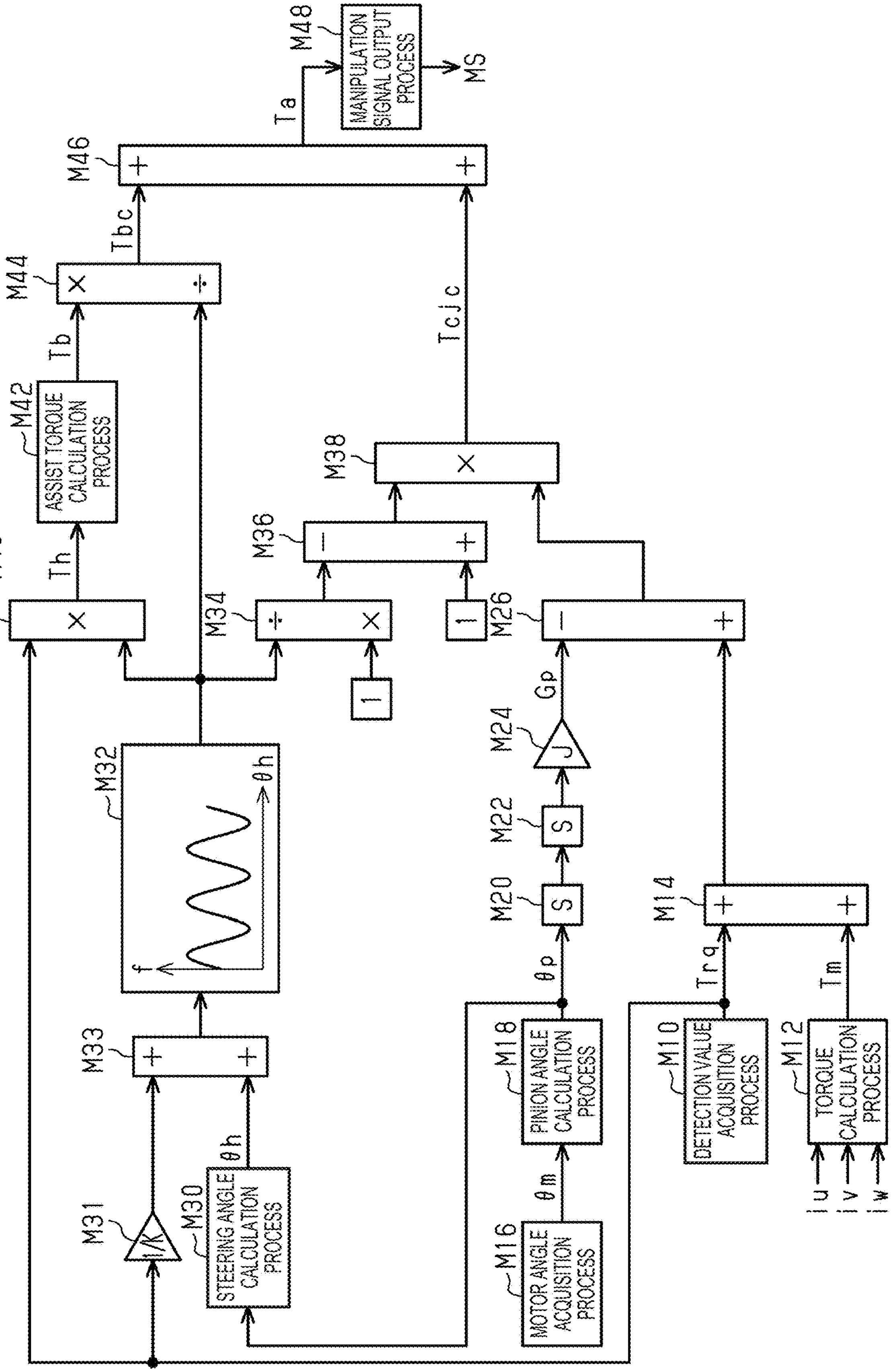

M48
MANIPULATION SIGNAL OUTPUT PROCESS
MS
Ta
M46
Tbc
M44
Tb
M42
ASSIST TORQUE CALCULATION PROCESS
Th
M40
Tcjc
M38
M36
M34
M32
θh
f
M33
M31
1/K
M30
STEERING ANGLE CALCULATION PROCESS
θh
M26
Gp
M24
J
M22
S
M20
S
θp
M18
PINION ANGLE CALCULATION PROCESS
θm
M16
MOTOR ANGLE ACQUISITION PROCESS
M14
Trq
Tm
M10
DETECTION VALUE ACQUISITION PROCESS
M12
TORQUE CALCULATION PROCESS
iu
iv
iw

FIG. 4

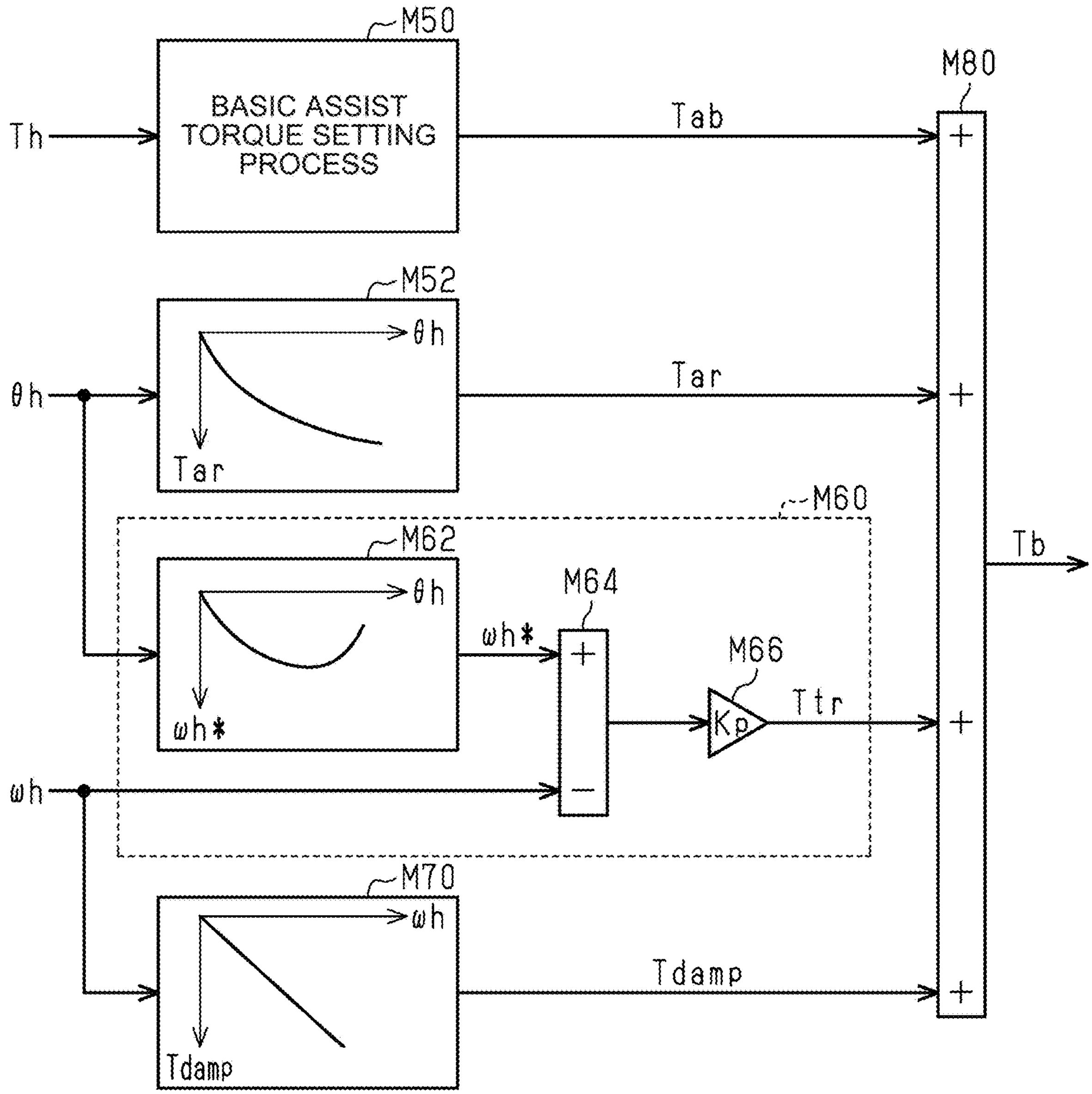

M50
BASIC ASSIST TORQUE SETTING PROCESS
Th
Tab
M80
M52
θh
θh
Tar
Tar
M60
M62
θh
ωh*
ωh*
M64
+
−
M66
Kp
Ttr
Tb
ωh
M70
ωh
Tdamp
Tdamp
+
+
+
+

FIG. 5

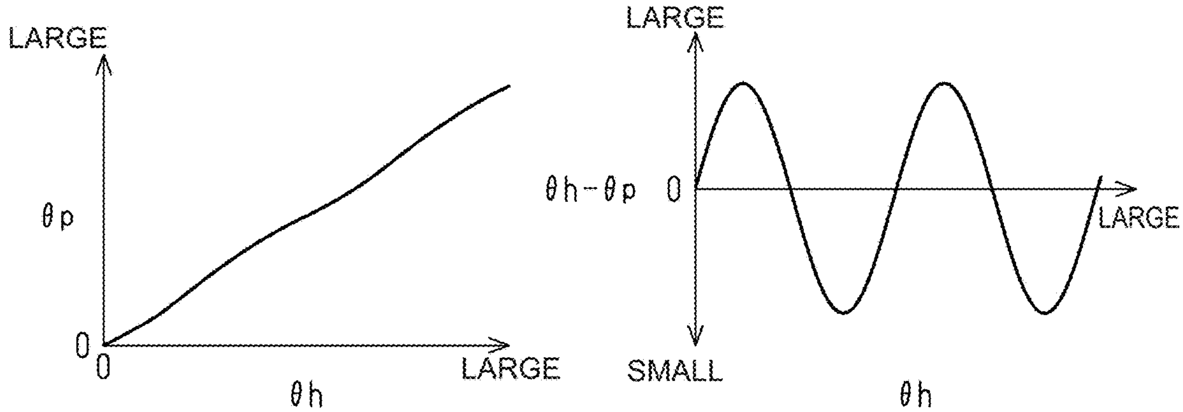
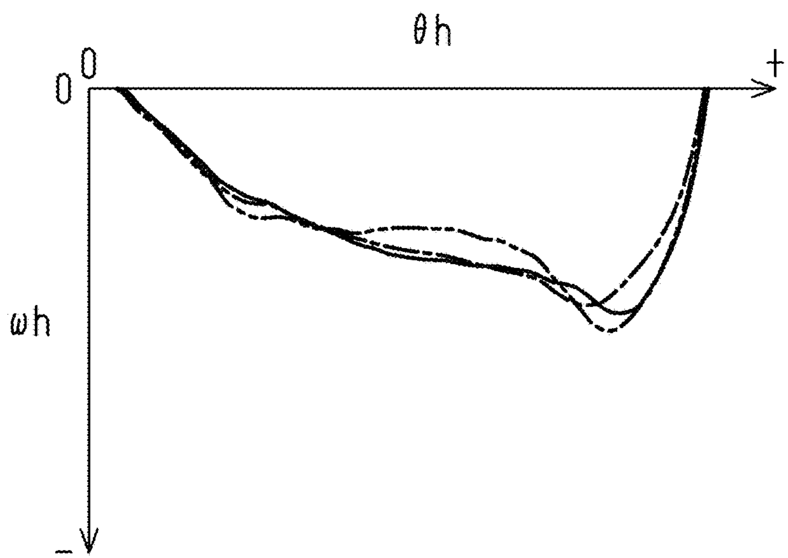


FIG. 6



TURNING CONTROL DEVICE

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority to Japanese Patent Application No. 2024-020171 filed on Feb. 14, 2024. The disclosure of the above-identified application, including the specification, drawings, and claims, is incorporated by reference herein in its entirety.

BACKGROUND

1. Technical Field

[0002] The present disclosure relates to a turning control device.

2. Description of Related Art

[0003] For example, Japanese Unexamined Patent Application Publication No. 2003-205846 (JP 2003-205846 A) describes a device that transmits the torque of a steering wheel to a turning wheel through a steering shaft, an intermediate shaft, and a transmitting shaft. The steering shaft and the intermediate shaft, and the intermediate shaft and the transmitting shaft, are each coupled by a universal joint. Further, the device includes a motor that applies a torque to the intermediate shaft.

[0004] Further, the torque of an assist motor that assists the manipulation of the steering wheel is controlled depending on a value resulting from adding an adjusting torque to an assist torque depending on a steering torque. The adjusting torque includes a torque depending on a steering angle or a time-differential value of the steering angle. Examples of the adjusting torque include a torque that is set depending on the steering angle for returning the steering angle to a neutral position when hands are disengaged from the steering wheel.

SUMMARY

[0005] In the case where the universal joint is included as described above, the ratio between the steering angle that is the rotation angle of the steering shaft and the rotation angle of the transmitting shaft varies depending on the steering angle. The inventor has studied the giving of the torque of the assist motor to a position that is closer to the turning wheel than to the universal joint. In that case, when the adjusting torque is set depending on the rotational angle of the transmitting shaft that is determined depending on the rotation angle of the assist motor, the adjusting torque can unintentionally vary depending on the steering angle. The variation can give a feeling of strangeness to a driver.

[0006] A turning control device according to an aspect of the present disclosure is configured to control a turning device. The turning device includes a steering wheel, an input shaft, an intermediate shaft, an output shaft, a first Cardan joint, a second Cardan joint, an assist motor, and a turning wheel. The input shaft is coupled to the steering wheel. The first Cardan joint is a member that couples the input shaft and the intermediate shaft. The second Cardan joint is a member that couples the intermediate shaft and the output shaft. The turning wheel is configured such that a steering torque input to the steering wheel is transmitted through the input shaft, the intermediate shaft, and the output shaft. The assist motor is configured to apply a torque to a position that is closer to the turning wheel than to the second Cardan joint. The turning control device includes a processor. The processor is configured to execute a turning-corresponding angle acquisition process, a rudder angle variable estimation process, a basic assist torque setting process, an adjusting torque calculation process, and a manipulation process. The turning-corresponding angle acquisition process is a process of acquiring a turning-corresponding angle depending on a detection value of a sensor as an input variable. The turning-corresponding angle is a variable indicating a turning angle of the turning wheel. The detection value of the sensor is a detection value of a physical amount at the position that is closer to the turning wheel than to the second Cardan joint. The rudder angle variable estimation process is a process of estimating the value of a rudder angle variable based on the turning-corresponding angle as an input variable. The rudder angle variable is a variable indicating a steering angle or a time-differential value of the steering angle. The steering angle is the angle of the steering wheel. The basic assist torque setting process is a process of setting the value of a basic assist torque variable depending on the steering torque. The adjusting torque calculation process is a process of calculating the value of an adjusting torque variable based on the value of the rudder angle variable as an input variable. The manipulation process includes a process of manipulating a drive circuit of the assist motor, so as to control the torque of the assist motor to a torque depending on the sum of a torque indicated by the value of the basic assist torque variable and a torque indicated by the value of the adjusting torque variable.

[0007] In the above configuration, the ratio between the turning-corresponding angle and the steering angle periodically varies depending on the steering angle. Hence, in the above configuration, the value of the adjusting torque variable is calculated using the value of the rudder angle variable estimated by the rudder angle variable estimation process. Therefore, the value of the adjusting torque variable can be set to an appropriate value depending on the steering angle or the change rate of the steering angle.

[0008] In the turning control device according to the aspect of the present disclosure, the rudder angle variable may include a variable indicating the steering angle. The manipulation process may be a process of controlling the torque of the assist motor to a torque depending on a value resulting from dividing the sum of the torque indicated by the value of the basic assist torque variable and the torque indicated by the value of the adjusting torque variable by the value of a ratio variable. The ratio variable may be a variable that periodically varies depending on the value of the variable indicating the steering angle as an input variable and that indicates the ratio of the steering torque to a torque at the position that is closer to the turning wheel than to the second Cardan joint.

[0009] The value of the above ratio variable varies depending on the steering angle. Hence, in the above configuration, the torque of the assist motor is controlled to the torque depending on the value resulting from dividing the sum of the torque indicated by the value of the basic assist torque variable and the torque indicated by the value of the adjusting torque variable by the value of the ratio variable. Thereby, it is possible to restrain the variation in the torque that is applied to the steering wheel when the above sum is an amount that does not periodically vary depending on the steering angle.

[0010] In the turning control device according to the aspect of the present disclosure, the rudder angle variable may include a variable indicating the steering angle and a variable indicating the time-differential value of the steering angle. The adjusting torque calculation process may include a target backing process. The target backing process may include a process of setting a target value of the variable indicating the time-differential value, depending on the value of the variable indicating the steering angle as an input variable, and a process of setting the value of a target backing torque variable, depending on a manipulated amount in a feedback control in which the variable indicating the time-differential value is a controlled amount and the target value is a target value of the controlled amount. The adjusting torque variable may include the target backing torque variable.

[0011] The above target value needs to be set to a value indicating an appropriate steering angle velocity depending on the steering angle. However, in the case where the target value is determined based on the turning-corresponding angle, the target value can unintentionally vary depending on the steering angle. Hence, in the above configuration, the variable indicating the steering angle is employed as an input variable in the target backing process. Thereby, the target value can be set to an appropriate value depending on the steering angle.

[0012] In the turning control device according to the aspect of the present disclosure, the rudder angle variable may include a variable indicating the steering angle. The adjusting torque calculation process may include an active return process. The active return process includes a process of calculating the value of a return torque variable for returning the steering angle to a neutral position, based on the variable indicating the steering angle as an input variable. The adjusting torque variable may include the return torque variable.

[0013] The above active return process is a process of setting an appropriate torque for returning the steering angle to the neutral position, depending on the steering angle. However, in the case where the value of the return torque variable is determined based on the turning-corresponding angle, the value of the return torque variable can unintentionally vary. Hence, in the above configuration, the variable indicating the steering angle is employed as an input variable in the active return process. Thereby, it is possible to restrain the value of the return torque variable from unintentionally varying.

[0014] In the turning control device according to the aspect of the present disclosure, the rudder angle variable may include a variable indicating the time-differential value of the steering angle. The adjusting torque calculation process may include a damping process. The damping process may be a process of calculating the value of a damping torque variable, based on the value of the variable indicating the time-differential value as an input variable. The damping torque variable may be a variable that has the reverse sign of the time-differential value. The adjusting torque variable may include the damping torque variable.

[0015] The above damping process is a process of setting an appropriate torque for giving stickiness to the manipulation of the steering wheel, depending on the steering angle velocity. However, in the case where the value of the damping torque variable is determined based on the time-differential value of the turning-corresponding angle, the value of the damping torque variable can unintentionally vary because of the difference between the steering angle velocity and the time-differential value of the turning-corresponding angle. Hence, in the above configuration, the variable indicating the time-differential value of the steering angle is employed as an input variable in the damping process. Thereby, it is possible to restrain the value of the damping torque variable from unintentionally varying.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] Features, advantages, and technical and industrial significance of exemplary embodiments of the present disclosure will be described below with reference to the accompanying drawings, in which like signs denote like elements, and wherein:

[0017] FIG. **1** is a diagram showing the configuration of a turning control system according to an embodiment;

[0018] FIG. **2** is a diagram showing the configuration of a first Cardan joint according to the embodiment;

[0019] FIG. **3** is a block diagram showing processes that are executed by a control device according to the embodiment;

[0020] FIG. **4** is a block diagram showing details of an assist amount setting process of the processes shown in FIG. **3**;

[0021] FIG. **5** is a diagram exemplifying the relation between a pinion angle and a handle angle according to the embodiment; and

[0022] FIG. **6** is a time chart exemplifying the effect of the embodiment.

DETAILED DESCRIPTION OF EMBODIMENTS

[0023] An embodiment will be described below with reference to the drawings.

System Configuration

[0024] As shown in FIG. **1**, the turning device **10** is a device that turns turning wheels **36** in the cooperation between the steering torque that is input to a steering wheel **12** by a driver and the dynamic power of a turning actuator **40**. The turning device **10** is an electric power steering device. Hereinafter, manipulating the steering wheel **12** in the right direction or the left direction is referred to as "steering".

[0025] The steering wheel **12** is fixed to a column shaft **14**. The column shaft **14** is mechanically coupled to an intermediate shaft **18** through a first Cardan joint **16**. The intermediate shaft **18** has a well-known contractible configuration. Of two end portions of the intermediate shaft **18** in the axial direction of the intermediate shaft **18**, an end portion on the reverse side of an end portion that is coupled to the first Cardan joint **16** is coupled to a pinion shaft **22** through a second Cardan joint **20**. The column shaft **14** is an example of the input shaft.

[0026] The pinion shaft **22** is disposed so as to have a predetermined crossing angle with a rack shaft **30**. A rack-and-pinion mechanism **32** is configured by the engagement between a rack tooth **30***a* formed on the rack shaft **30** and a pinion tooth **22***a* formed on the pinion shaft **22**. Further, tie rods **34** are coupled to both ends of the rack shaft **30**. Distal ends of the tie rods **34** are coupled to unillustrated knuckles to which the turning wheels **36** are secured. By the rack-and-pinion mechanism **32**, the rotation manipulation of the steering wheel **12** is transformed into the displacement action of the rack shaft **30** in the axial direction of the rack shaft **30**. The displacement action in the axial direction is transmitted to the knuckles through the tie rods **34**, and thereby, the turning angle of the turning wheel **36** is changed. The turning angle is the moving angle of a tire that is the turning wheel **36**. The pinion shaft **22** is an example of the output shaft.

[0027] The turning actuator **40** includes an assist motor **42** that is a drive source, a transmission mechanism **44** that transmits the torque of the assist motor **42**, and a ball screw mechanism **46**. The ball screw mechanism **46** transforms the torque of the assist motor **42** that is transmitted through the transmission mechanism **44**, into the power for the displacement of the rack shaft **30** in the axial direction. As an example, the assist motor **42** is a three-phase brushless motor. The output voltage of an inverter **60** is applied to a terminal of the assist motor **42**.

[0028] The control device **50** includes a PU **52** and a storage device **54**. The PU **52** is a software processing device that includes at least one of a CPU, a GPU, and the like.

[0029] The control device **50** manipulates the inverter **60** for controlling the controlled amount of the turning wheel **36** as a controlled object. For the control of the controlled amount, the control device **50** refers to a rotation angle θm of the assist motor **42** that is detected by a rotation angle sensor **70**. Further, the control device **50** refers to electric currents iu, iv, iw that are output by the inverter **60**. The electric currents iu, iv, iw may be detected as voltage drop amounts at shunt resistors provided on respective legs of the inverter **60**. Further, the control device **50** refers to a detection value Trq of a torque sensor **72**. The detection value Trq is a detection value of the torque that is applied to the pinion shaft **22**. The torque sensor **72** is a sensor that detects the torque depending on the torsion angle of a well-known torsion bar provided at the pinion shaft **22**. The inverter **60** is an example of the drive circuit.

[0030] A superior ECU **80** is an electronic control device that generates a command that is relevant to the control of the vehicle and that is superior to the control device **50**. The superior ECU **80** refers to a steering angle θh that is detected by a rudder angle sensor **82**. The steering angle θh is the rotational angle of the steering wheel **12**. In other words, the steering angle θh is the rotational angle of the column shaft **14**.

[0031] The control device **50** and the superior ECU **80** can communicate with each other. Moreover, the control device **50** can receive the steering angle θh that is acquired by the superior ECU **80**. The sampling period of the steering angle θh is longer than the sampling period of the rotation angle θm.

Cardan Joint

[0032] FIG. **2** shows the configuration of the first Cardan joint **16**.

[0033] The first Cardan joint **16** includes a first yoke **16***a*, a second yoke **16***b*, and a joint cross **16***c*. The joint cross **16***c* has a cross shape. The joint cross **16***c* couples the first yoke **16***a* and the second yoke **16***b* in a mutually rotatable manner. The first yoke **16***a* is fastened to an end portion of the column shaft **14** by a bolt. The first yoke **16***a* may be welded to the end portion of the column shaft **14**. The second yoke **16***b* is fixed to an end portion of the intermediate shaft **18** by welding.

[0034] The configuration of the second Cardan joint **20** is the same as the configuration of the first Cardan joint **16**, and therefore, the description about the configuration of the second Cardan joint **20** is omitted.

Variation in Torque Due to Cardan Joint

[0035] A ratio f(θh)(=Th/Trq) between a steering torque Th that is a torque that is applied to the steering wheel **12** and a torque that is applied to the pinion shaft **22** has a relation that is expressed as the following Expression (c1).

$$f(\theta h)=\frac{\cos\alpha 1\cdot\cos\alpha 2}{\left(1-\sin^2\alpha 1\cdot\sin^2\theta h\right)\cdot\left[1-\sin^2\alpha 2\{\sin(\arctan(\tan\theta h\cdot\cos\alpha 1)+\phi\}\right]^2}\tag{c1}$$

[0036] Here, a bend angle α**1** of the first Cardan joint **16**, a bend angle α**2** of the second Cardan joint **20**, and a phase difference y are used. The bend angle α**1** of the first Cardan joint **16** is the angle between the axial direction of the column shaft **14** and the axial direction of the intermediate shaft **18**. Further, the bend angle α**2** of the second Cardan joint **20** is the angle between the axial direction of the intermediate shaft **18** and the axial direction of the pinion shaft **22**. The phase difference ψ is "90−ξ+ε". Here, "ξ" is the angle between a plane parallel to both of the axial direction of the column shaft **14** and the axial direction of the intermediate shaft **18** and a plane parallel to both of the axial direction of the intermediate shaft **18** and the axial direction of the pinion shaft **22**. Further, "ε" is the phase difference between the second yoke **16***b* that is of the two yokes of the first Cardan joint **16** and that is on the intermediate shaft **18** side and the yoke that is of the two yokes of the second Cardan joint **20** and that is on the intermediate shaft **18** side. The phase difference indicates a gap in rotational angle around the axial direction of the intermediate shaft **18**.

[0037] According to the above Expression (c1), for example, in the case where the torque that is applied to the pinion shaft **22** is constant without depending on the steering angle θh, the steering torque Th can vary depending on the steering angle θh. In the case where the steering torque Th varies depending on the steering angle θh, the driver can have a feeling of strangeness about the manipulation of the steering wheel **12**. A control for coping with this will be described below.

Torque Control for Assist Motor

[0038] FIG. **3** shows processes that are executed by the control device **50**. The processes shown in FIG. **3** are realized when the PU **52** repeatedly executes an assist control program **54***a* stored in the storage device **54**, for example, with a predetermined period.

[0039] A detection value acquisition process M**10** is a process of acquiring the detection value Trq by the torque sensor **72** with a predetermined sampling period.

[0040] A torque calculation process M**12** is a process of calculating a motor torque Tm that is a torque generated in the assist motor **42**, based on the electric currents iu, iv, iw that flow through the assist motor **42**. Actually, the motor torque Tm is a torque resulting from converting the torque of the assist motor **42** into the torque of the pinion shaft **22**.

[0041] An addition process M**14** is a process of adding the detection value Trq and the motor torque Tm.

[0042] A motor angle acquisition process M**16** is a process of calculating the rotation angle θm of a rotation shaft of the assist motor **42** with a predetermined sampling period. The motor angle acquisition process M**16** is an example of a steering angle variable acquisition process.

[0043] A pinion angle calculation process M**18** is a process of calculating a pinion angle θp that is the rotation angle of the pinion shaft **22**, based on the rotation angle θm as an input variable.

[0044] A differential operator M**20** is a process of calculating a first-order time-differential value based on the pinion angle θp as an input variable. The pinion angle θp is an example of the turning-corresponding angle.

[0045] A differential operator M**22** is a process of calculating a first-order time-differential value based on the output value of the differential operator M**20** as an input variable.

[0046] An inertia term calculation process M**24** is a process of outputting an inertia term Gp that is a value resulting from multiplying the output value of the differential operator M**22** by an inertia coefficient J. The output value of the differential operator M**22** is a second-order time-differential value of the pinion angle θp, and therefore, the output value of the inertia term calculation process M**24** corresponds to the inertia torque of the turning device **10**.

[0047] A subtraction process M**26** is a process of subtracting the output value of the inertia term calculation process M**24** from the output value of the addition process M**14**.

[0048] A steering angle calculation process M**30** is a process of calculating the steering angle θh based on the pinion angle θp as an input variable. The steering angle calculation process M**30** is a process of calculating the steering angle θh using a mapping that is prescribed by mapping data **54***b* stored in the storage device **54** shown in FIG. **1**. The mapping is a mapping that receives the pinion angle θp as an input and that outputs the steering angle θh. The mapping is prescribed by the following Expression (c2)

$$\theta h = -\arctan\frac{\tan\left[-\arctan\left\{\frac{\tan(\theta p + \arctan(\tan\phi\cdot\cos\alpha 2))}{\cos\alpha 2}\right\} + \phi\right]}{\cos\alpha 1} \quad \text{(c2)}$$

[0049] The above expression is derived by applying an expression that prescribes the relation between the rotation angles and bend angles of a pair of the yokes of a Cardan joint, to the first Cardan joint **16** and the second Cardan joint **20**.

[0050] That is, the above expression is derived by using a simultaneous equation including the following expressions (c3) and (c4).

$$\tan\theta 2 = \cos\alpha 1 \cdot \tan\theta h \quad \text{(c3)}$$

$$\tan(\theta p') = \cos\alpha 2 \cdot \tan(\theta 2 + \psi) \quad \text{(c4)}$$

[0051] The above "θ2" is the rotation angle of the intermediate shaft **18**. Further, "θp" indicates the phase difference of the pinion angle θp from "θh". Specifically, the following Expression (c5) is derived from Expression (c3) and Expression (c4).

$$\theta p' = \arctan(\tan[\arctan\{\tan(\theta h)\cdot\cos(\alpha 1)\} + \psi]\cdot\cos(\alpha 2)) \quad \text{(c5)}$$

[0052] Accordingly, the pinion angle θp is expressed as the following Expression (c6).

$$\theta p = \theta p' - \arctan\{\tan(\psi)\cdot\cos(\alpha 2)\} \quad \text{(c6)}$$

[0053] The above Expression (c2) is derived by eliminating Op' from Expression (c5) and Expression (c6).

[0054] The mapping data **54***b* includes data about values of the first bend angle α**1**, the second bend angle α**2**, and the phase difference ψ, and the like. The above Expression (c1) is calculated based on the ratio between a first-order time-differential value of the steering angle θh and the first-order time-differential value of the pinion angle θp and an expression for energy conservation. The ratio between the first-order time-differential value of the steering angle θh and the first-order time-differential value of the pinion angle θp can be calculated by the time differential of the above Expression (c2).

[0055] A rigidity coefficient multiplication process M**31** is a process of multiplying the detection value Trq by the reciprocal of a rigidity coefficient K. The rigidity coefficient K is a coefficient indicating the torsional rigidity of the torsion bar. A steering angle correction process M**33** is a process of correcting the steering angle θh by multiplying the steering angle θh output by the steering angle calculation process M**30** by the output value of the rigidity coefficient multiplication process M**31**. The steering angle θh determined from the above Expression (c2) deviates from the actual steering angle by the torsional amount of the torsion bar. An amount resulting from multiplying the detection value Trq by the reciprocal of the rigidity coefficient K is an estimated value of the torsional amount of the torsion bar.

[0056] A ratio calculation process M**32** is a process of calculating the ratio f(θh) between the torque of the pinion shaft **22** and the steering torque Th. For example, the ratio f(θh) may be expressed as the above Expression (c1). That is, the ratio f(θh) may be calculated by the PU **52** using Expression (c1), by storing data prescribing the above Expression (c1) in the storage device **54**. Further, for example, the map computation of the ratio f(θh) may be performed by the PU **52**, in a state where map data is previously stored in the storage device **54**. The map data is data in which the steering angle θh is adopted as an input variable and the ratio f(θh) is adopted as an output variable.

[0057] The map data is combination data of discrete values of the input variable and values of the output variable that correspond to the respective values of the input variable. Further, in the map computation, in the case where the value of the input variable coincides with one of the values of the input variable in the map data, the corresponding value of the output variable in the map data may be adopted as the computation result. Further, in the map computation, in the case where the value of the input variable does not coincide with any of the values of the input variable in the map data, a value obtained by the interpolation with a plurality of values of the output variable that is included in the map data may be adopted as the computation result. Alternatively, in the map computation, in the case where the value of the input variable does not coincide with any of the values of the input variable in the map data, the closest value of the plurality of values of the input variable that is included in the map data may be adopted, and the corresponding value of the output variable in the map data may be adopted as the computation result.

[0058] A division process M**34** is a process of calculating the reciprocal of the ratio f(θh).

[0059] A subtraction process M**36** is a process of subtracting the output value of the division process M**34** from "1".

[0060] A compensation torque calculation process M**38** is a process of calculating a Cardan joint compensation torque Tcjc by multiplying the output value of the subtraction process M**26** and the output value of the subtraction process M**36**.

[0061] A steering torque calculation process **M40** is a process of calculating the steering torque Th by multiplying the detection value Trq by the ratio f(θh).

[0062] An assist torque calculation process M**42** is a process of calculating an assist torque Tb based on the steering torque Th as an input variable. That is, the assist torque calculation process M**42** is a process of changing the assist torque Tb depending on driver's steering intention indicated by the steering torque Th.

[0063] A variation assist torque calculation process M**44** is a process of calculating a variation assist torque Tbc by dividing the assist torque Tb by the ratio f(θh).

[0064] A superimposition process M**46** is a process of calculating an assist torque Ta by adding the variation assist torque Tbc and the Cardan joint compensation torque Tcjc.

[0065] A manipulation signal output process M**48** is a process of generating and outputting a manipulation signal MS of the inverter **60** for controlling the torque of the assist motor **42** to the assist torque Ta. Actually, the manipulation signal MS is a manipulation signal for each switching element of the inverter **60**. The manipulation signal output process M**48** is an example of the manipulation process.

Details of Assist Torque Calculation Process M**42**

[0066] FIG. **4** shows details of the assist torque calculation process M**42**.

[0067] A basic assist torque setting process M**50** is a process of calculating a basic assist torque Tab based on the steering torque Th as an input variable. The basic assist torque setting process M**50** is a process of changing the basic assist torque Tab depending on the steering torque Th, under the following condition. The condition is a condition that the absolute value of the basic assist torque Tab in the case where the absolute value of the steering torque Th is large is larger than or equal to the absolute value of the basic assist torque Tab in the case where the absolute value of the steering torque Th is small. The basic assist torque setting process M**50** is an example of the basic assist torque setting process.

[0068] In the description of "B is changed depending on A under the condition that B in the case where A is large is larger than or equal to B in the case where A is small", the case where A is large and the case where A is small mean a relative magnitude relation in the comparison of the two cases. For example, "the case where A is large" corresponds to the case of "A is a first value", and "the case where A is small" corresponds to the case of "A is a second value smaller than the first value". Moreover, the above description means that B in the case where A is the first value is sometimes larger than B in the case where A is the second value depending on the setting of the first value and the second value. Further, the above description means that B is changed depending on A such that A in the case where B is large becomes larger than A in the case where B is small.

[0069] An active return process M**52** is a process of calculating an active return torque Tar based on the steering angle θh as an input variable. The active return torque Tar is a torque for returning the steering angle θh to a neutral position. Accordingly, the sign of the active return torque Tar is the reverse of the sign of the steering angle θh. The active return process M**52** is a process of changing the active return torque Tar depending on the steering angle θh, under the following condition. The condition is a condition that the absolute value of the active return torque Tar in the case where the absolute value of the steering angle θh is large is larger than or equal to the absolute value of the active return torque Tar in the case where the absolute value of the steering angle θh is small. The active return torque Tar is an example of the return torque variable.

[0070] A target backing process M**60** is a process of calculating a target backing torque Ttr based on the steering angle and a steering angle velocity ωh as input variables. The target backing torque Ttr is a manipulated amount for controlling the steering angle velocity ωh when the steering angle θh is returned to the neutral position such that the steering angle velocity ωh gets close to a target steering angle velocity ωh*. The target backing process M**60** includes a target angle velocity setting process M**62**, a deviation calculation process M**64**, and a proportional element M**66**. The steering angle velocity ωh is an example of the variable indicating the time-differential value. The target backing torque Ttr is an example of the target backing torque variable. The target steering angle velocity ωh* is an example of the target value.

[0071] The target angle velocity setting process M**62** is a process of setting the target steering angle velocity ωh* based on the steering angle θh as an input variable. Specifically, the target angle velocity setting process M**62** may be a process in which the PU **52** performs the map computation of the target steering angle velocity ωh* in a state where map data is stored in the storage device **54**. The map data is data in which the steering angle θh is adopted as an input variable and the target steering angle velocity ωh* is adopted as an output variable. The deviation calculation process M**64** is a process of calculating the difference between the target steering angle velocity ωh* and the steering angle velocity ωh. The proportional element M**66** is a process of substituting a value resulting from multiplying the output variable of the deviation calculation process M**64** by a gain Kp, in the target backing torque Ttr.

[0072] A damping process M**70** is a process of calculating a damping torque Tdamp based on the steering angle velocity ωh as an input variable. The damping torque Tdamp is a torque for attenuating the vibration of a manipulation system by giving stickiness to the manipulation of the steering wheel **12**. The sign of the damping torque Tdamp is the reverse of the sign of the steering angle velocity ωh. The damping process M**70** is a process of calculating the damping torque Tdamp depending on the steering angle velocity ωh, under the following condition. The condition is a condition that the absolute value of the damping torque Tdamp in the case where the absolute value of the steering angle velocity ωh is large is larger than or equal to the absolute value of the damping torque Tdamp in the case where the absolute value of the steering angle velocity ωh is small. The active return process M**52**, the target backing process M**60**, and the damping process M**70** constitute an example of the adjusting torque calculation process. The damping torque Tdamp is an example of the damping torque variable.

[0073] A synthesis process M**80** is a process of substituting the sum of the basic assist torque Tab, the active return torque Tar, the target backing torque Ttr, and the damping torque Tdamp, in the assist torque Tb.

Operation and Effect of Embodiment

[0074] The following Expression (c5) is a motion equation for the pinion shaft **22**.

$$Trq + Tm = Gp + Tp \tag{c5}$$

[0075] Here, the inertia term Gp is an inertia term of the torque of the pinion shaft **22**. Further, a torque Tp is a torque other than the inertia term Gp that is applied to the pinion shaft **22**.

[0076] The above Expression (c5) can be expressed as the following Expression (c6).

$$Trq = Gp + Tp - Tm \tag{c6}$$

[0077] When the ratio f(θh) in the above Expression (c1) is used, the steering torque Th can be expressed as the following Expression (c7).

$$Th = f(\theta h) \cdot (Gp + Tp - Tm) \tag{c7}$$

[0078] The motor torque Tm that is the assist torque is expressed as Expression (c8).

$$Tm = Tbc + \{1 - (1/f(\theta h))\} \cdot Tp \tag{c8}$$

[0079] When the above Expression (c8) is substituted in the above Expression (c7), the following Expression (c9) is obtained.

$$Tm = Tp + f(\theta h) \cdot (Gp - Tbc) \tag{c9}$$

[0080] When "Tbc=Tb/f(θh)" is substituted in the above Expression (c9), the following Expression (c10) is obtained.

$$Th = Tp - Tb + f(\theta h) \cdot Gp \tag{c10}$$

[0081] In the above Expression (c10), when the term "f(θh). Gp" is ignored, the ratio between the steering torque Th and "Tp–Tb" does not depend on the steering angle θh.

[0082] Therefore, when the variation in the torque Tp depending on the steering angle θh is small, it is possible to restrain the steering torque Th from varying depending on the steering angle θh.

[0083] Therefore, in the embodiment, the motor torque Tm is set to the sum of the variation assist torque Tbc and the Cardan joint compensation torque Tcjc. That is, the Cardan joint compensation torque Tcjc is the second term in the right-hand member of the above Expression (c8).

[0084] In each of the active return process M**52**, the target backing process M**60**, and the damping process M**70**, the manipulated object is the assist motor **42**. Therefore, it is naturally thought that the input variables in the active return process M**52**, the target backing process M**60**, and the damping process M**70** are set to the pinion angle θp or the time-differential value of the pinion angle θp. According to the above Expression (c2), the relation between the steering angle θh and the pinion angle θp has non-linearity. The left side of FIG. **5** shows the non-linearity relation. Further, the right side of FIG. **5** shows the difference between the steering angle θh and the pinion angle θp with respect to the steering angle θh.

[0085] Each of the active return process M**52**, the target backing process M**60**, and the damping process M**70** is a process for controlling the behavior of the steering wheel **12**. Therefore, if the input variable in each process is the pinion angle θp or the time-differential value of the pinion angle θp, there is fear that the behavior of the steering wheel **12** cannot be appropriately controlled.

[0086] In this respect, in the embodiment, in each of the active return process M**52**, the target backing process M**60**, and the damping process M**70**, the input variable is set to the steering angle θh or the steering angle velocity ωh. Thereby, the active return torque Tar, the target backing torque Ttr, and the damping torque Tdamp as adjusting torques can be set to appropriate values depending on the steering angle θh or the change rate of the steering angle θh.

[0087] FIG. **6** exemplifies the behavior of the steering angle θh due to the target backing process in each of the embodiment and a comparative example. In FIG. **6**, the one-dot chain line shows the transition of the target steering angle velocity ωh*. In FIG. **6**, the solid line shows the transition of the steering angle velocity ωh according to the embodiment. In FIG. **6**, the two-dot chain line shows a comparative example in which the pinion angle θp and the time-differential value of the pinion angle θp are used as input variables in the target backing process M**60**, instead of the steering angle θh and the steering angle velocity ωh.

[0088] As shown in FIG. **6**, in the embodiment, the trackability of the steering angle velocity ωh to the target steering angle velocity ωh* is improved compared to the comparative example.

[0089] With the above-described embodiment, an effect described below is further obtained.

[0090] (1) The PU **52** calculates the variation assist torque Tbc by dividing the assist torque Tb by the ratio f(θh). The ratio f varies depending on the steering angle θ*h*. Hence, in the embodiment, the torque of the assist motor **42** is controlled to the torque depending on the value resulting from dividing the assist torque Tb by the ratio f(θh). Thereby, it is possible to restrain the variation in the torque that is applied to the steering wheel in the case where the assist torque Tb is an amount that does not periodically vary depending on the steering angle θh. The ratio f is an example of the ratio variable.

OTHER EMBODIMENTS

[0091] The embodiment can be carried out while being modified as follows. The embodiment and the following modifications can be carried out while being combined with each other as long as there is no technical inconsistency.

Turning-Corresponding Angle Acquisition Process

[0092] In the above embodiment, the turning-corresponding angle acquisition process is a process of acquiring the pinion angle θp as the variable indicating the turning angle, but the applicable embodiment is not limited to this. For example, the turning-corresponding angle acquisition process may be a process of acquiring the displacement amount of the rack shaft **30** in the axial direction of the rack shaft **30**.

Basic Assist Torque Setting Process

[0093] The assist torque calculation process M**42** of calculating the assist torque Tb that does not depend on the steering angle θh is not essential. For example, a process of directly calculating the variation assist torque Tbc using the steering torque Th and the steering angle θh as inputs may be employed.

Target Backing Torque Variable

[0094] It is not essential that the target backing variable that is the output variable in the target backing process is the target backing torque Ttr. For example, the target backing variable may be a command value of the electric current that flows through the assist motor **42**. Specifically, for example, in the case where the assist motor **42** is a SPM, the target backing variable may be a q-axis current.

Return Torque Variable

[0095] It is not essential that the return torque variable that is the output variable in the active return process is the active return torque Tar. For example, the return torque variable may be a command value of the electric current that flows through the assist motor **42**. Specifically, for example, in the case where the assist motor **42** is the SPM, the return torque variable may be the q-axis current.

Damping Variable

[0096] It is not essential that the damping torque variable as the output variable in the damping process is the damping torque Tdamp. For example, the damping torque variable may be a command value of the electric current that flows through the assist motor **42**. Specifically, for example, in the case where the assist motor **42** is the SPM, the damping torque variable may be the q-axis current.

Adjusting Torque Calculation Process

[0097] It is not essential that the adjusting torque calculation process of calculating the value of the adjusting torque variable based on the steering angle θh or the steering angle velocity ωh as the input variable includes the target backing process, the active return process, and the damping process. For example, the adjusting torque calculation process may include only two processes of the three processes. Further, for example, the adjusting torque calculation process may include only one process of the three processes.

[0098] The adjusting torque calculation process may include a process other than the above three processes. For example, the adjusting torque calculation process may include a process of calculating the value of a hysteresis torque variable having values that are different between cutting and cutting-back.

Manipulation Process

[0099] The input variable in the manipulation process is not limited to the two variables: the value of the adjusting torque variable and the value of the basic assist torque variable. For example, the input variable in the manipulation process may include a torque for restraining a torque ripple that is periodically generated depending on the rotational angle due to the structure of a mechanism that transmits the torque of the assist motor **42** to the turning wheels **36**.

[0100] First Bend Angle α**1**, Second Bend Angle α**2**

[0101] In the above embodiment, the first bend angle α**1** and the second bend angle α**2** are set to fixed values that are previously determined, but the applicable embodiment is not limited to this. For example, in the case where the height of the steering wheel **12** can be adjusted by the rotation of the column shaft **14** around a rotation center OT as shown by two-dot chain lines in FIG. **1**, the first bend angle α**1** and the second bend angle α**2** may be set depending on the rotation amount of the column shaft **14**. The cause of the change in the bend angles α**1**, α**2** is not limited to the change in tilt angle. For example, the cause of the change in the bend angles α**1**, α**2** may be the use of a telescopic function.

Turning Control Device

[0102] The control device **50** is not limited to a device that includes the PU **52** and the storage device **54** and that executes software processing. For example, a dedicated hardware circuit (for example, an ASIC) that executes at least some of the processes that are executed in the above embodiment may be included. That is, the turning control device only needs to include one processing circuit of the following (a) to (c). (a) A processing circuit including a processing device that executes all of the above processes in accordance with programs and a program storing device that stores programs, as exemplified by a ROM. (b) A processing circuit including a processing device that executes some of the above processes in accordance with programs, a program storing device, and a dedicated hardware circuit that executes the other processes. (c) A processing circuit including a dedicated hardware circuit that executes all of the above processes. A plurality of software processing circuits each of which a processing device and a program storing device may be provided, and a plurality of dedicated hardware circuits may be provided. That is, the above processes only need to be executed by a processing circuit that includes at least one of a single or a plurality of software processing circuits and a single or a plurality of dedicated hardware circuits.

Turning Device

[0103] The applicable embodiment is not limited to the configuration in which the rotation shaft of the assist motor

42 and the rack shaft 30 are disposed so as to be parallel to each other. For example, a second rack-and-pinion mechanism may be included separately from the rack-and-pinion mechanism 32, and the torque of the assist motor 42 may be applied through the second rack-and-pinion mechanism.

Others

[0104] It is not essential that the steering angle θh as the input in the ratio calculation process M32 is the output value of the steering angle correction process M33. For example, the steering angle θh output by the steering angle calculation process M30 may be adopted as the input in the ratio calculation process M32.

What is claimed is:

1. A turning control device configured to control a turning device, the turning device including:

a steering wheel;

an input shaft that is coupled to the steering wheel;

an intermediate shaft;

an output shaft;

a first Cardan joint that is a member that couples the input shaft and the intermediate shaft;

a second Cardan joint that is a member that couples the intermediate shaft and the output shaft;

a turning wheel configured such that a steering torque input to the steering wheel is transmitted through the input shaft, the intermediate shaft, and the output shaft; and

an assist motor configured to apply a torque to a position that is closer to the turning wheel than to the second Cardan joint,

the turning control device comprising a processor configured to execute:

a turning-corresponding angle acquisition process that is a process of acquiring a turning-corresponding angle depending on a detection value of a sensor as an input variable, the turning-corresponding angle being a variable indicating a turning angle of the turning wheel, the detection value of the sensor being a detection value of a physical amount at the position that is closer to the turning wheel than to the second Cardan joint;

a rudder angle variable estimation process that is a process of estimating a value of a rudder angle variable based on the turning-corresponding angle as an input variable, the rudder angle variable being a variable indicating a steering angle or a time-differential value of the steering angle, the steering angle being an angle of the steering wheel;

a basic assist torque setting process that is a process of setting a value of a basic assist torque variable depending on the steering torque;

an adjusting torque calculation process that is a process of calculating a value of an adjusting torque variable based on the value of the rudder angle variable as an input variable; and

a manipulation process that includes a process of manipulating a drive circuit of the assist motor, so as to control the torque of the assist motor to a torque depending on a sum of a torque indicated by the value of the basic assist torque variable and a torque indicated by the value of the adjusting torque variable.

2. The turning control device according to claim **1**, wherein:

the rudder angle variable includes a variable indicating the steering angle;

the manipulation process is a process of controlling the torque of the assist motor to a torque depending on a value resulting from dividing the sum of the torque indicated by the value of the basic assist torque variable and the torque indicated by the value of the adjusting torque variable by a value of a ratio variable; and

the ratio variable is a variable that periodically varies depending on a value of the variable indicating the steering angle as an input variable and that indicates a ratio of the steering torque to a torque at the position that is closer to the turning wheel than to the second Cardan joint.

3. The turning control device according to claim **1**, wherein:

the rudder angle variable includes a variable indicating the steering angle and a variable indicating the time-differential value of the steering angle;

the adjusting torque calculation process includes a target backing process;

the target backing process includes a process of setting a target value of the variable indicating the time-differential value, depending on a value of the variable indicating the steering angle as an input variable, and a process of setting a value of a target backing torque variable, depending on a manipulated amount in a feedback control in which the variable indicating the time-differential value is a controlled amount and the target value is a target value of the controlled amount; and

the adjusting torque variable includes the target backing torque variable.

4. The turning control device according to claim **1**, wherein:

the rudder angle variable includes a variable indicating the steering angle;

the adjusting torque calculation process includes an active return process;

the active return process includes a process of calculating a value of a return torque variable for returning the steering angle to a neutral position, based on the variable indicating the steering angle as an input variable; and

the adjusting torque variable includes the return torque variable.

5. The turning control device according to claim **1**, wherein:

the rudder angle variable includes a variable indicating the time-differential value of the steering angle;

the adjusting torque calculation process includes a damping process;

the damping process is a process of calculating a value of a damping torque variable, based on a value of the variable indicating the time-differential value as an input variable;

the damping torque variable is a variable that has a reverse sign of the time-differential value; and

the adjusting torque variable includes the damping torque variable.

* * * * *