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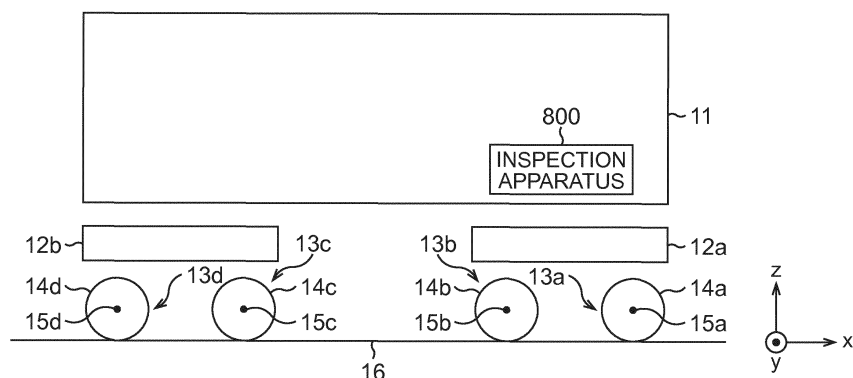
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(54) **INSPECTION SYSTEM, INSPECTION METHOD AND PROGRAM**

(57) An inspection apparatus (800) calculates an alignment irregularity amount by substituting angular displacements of wheel sets (13a to 13d) in a yawing direction, state variables derived by a filter, and a measured

value of a forward-and-backward-direction force into motion equations that describe yawings of the wheel sets (13a to 13d).

FIG. 1



Description

TECHNICAL FIELD

5 **[0001]** The present invention relates to an inspection system, an inspection method, and a program, and in particular, is ones to be suitable when used for inspecting a track of a railway vehicle.

BACKGROUND ART

10 **[0002]** When a railway vehicle travels on a track, the position of the track changes due to a load from the railway vehicle. When such a change in track occurs, the railway vehicle is liable to exhibit abnormal behavior. Thus, detection of abnormality of the track has been performed conventionally by causing a railway vehicle to travel on the track.

[0003] In Patent Literature 1, measuring a track irregularity amount by a three-point measuring method has been described. Further, in Patent Literature 2, there has been described that vibration data of a railway vehicle are applied, as observation data, to a model-based estimation method such as a Kalman filter, to thereby detect abnormal behavior of the railway vehicle.

CITATION LIST

20 PATENT LITERATURE

[0004]

Patent Literature 1: Japanese Laid-open Patent Publication No. 56-19404

25 Patent Literature 2: Japanese Laid-open Patent Publication No. 2005-67276

NON PATENT LITERATURE

[0005]

30 Non Patent Literature 1: "Railway vehicle dynamics The latest bogie technology" edited by The Japan Society of Mechanical Engineers, DENKISYA KENKYUKAI CO.,LTD., January, 2003, p. 15-p. 33

Non Patent Literature 2: Ping Li et al., "Estimation of railway vehicle suspension parameters for condition monitoring," Control Engineering Practice 15 (2007) p. 43-p. 55

SUMMARY OF INVENTION

TECHNICAL PROBLEM

40 **[0006]** However, the method described in Patent Literature 1 is a method to directly measure the track irregularity. Therefore, an expensive measuring apparatus is required. Further, the method described in Patent Literature 2 does not select state variables. Therefore, it is not easy to predict the track irregularity with high accuracy.

[0007] The present invention has been made in consideration of the above-described problems, and an object thereof is to enable accurate detection of track irregularity of a railway vehicle inexpensively.

SOLUTION TO PROBLEM

[0008] An inspection system of the present invention includes: a data acquisition means that acquires measured data being data of measured values to be measured by causing a railway vehicle including a vehicle body, a bogie, and a wheel set to travel on a track; a filter operation means that performs an operation using a filter performing data assimilation by using the measured data, a state equation, and an observation equation, and thereby determines state variables being variables to be determined in the state equation; and a track state calculation means that derives information reflecting a state of the track, in which the measured data contain measured values of accelerations of the bogie and the wheel set in a right and left direction and a measured value of a forward-and-backward-direction force, the right and left direction is a direction vertical to both a forward and backward direction being a direction along a traveling direction of the railway vehicle and an up and down direction being a direction vertical to the track, the forward-and-backward-direction force is a force in the forward and backward direction to occur in a member disposed between the wheel set and the bogie on which the wheel set is provided, and is a force to be determined according to a difference between an

angular displacement of the wheel set in a yawing direction and an angular displacement of the bogie on which the wheel set is provided in the yawing direction, the member is a member for supporting an axle box, the yawing direction is a pivoting direction with the up and down direction set as a pivot axis, the state equation is an equation described by using the state variables, the forward-and-backward-direction force, and a transformation variable, the state variables include a displacement and a velocity of the bogie in the right and left direction, an angular displacement and an angular velocity of the bogie in the yawing direction, an angular displacement and an angular velocity of the bogie in a rolling direction, a displacement and a velocity of the wheel set in the right and left direction, and an angular displacement of an air spring attached to the railway vehicle in the rolling direction, and do not include an angular displacement or an angular velocity of the wheel set in the yawing direction, the rolling direction is a pivoting direction with the forward and backward direction set as a pivot axis, the transformation variable is a variable that performs mutual transformation between the angular displacement of the wheel set in the yawing direction and the angular displacement of the bogie in the yawing direction, the observation equation is an equation described by using an observation variable and the transformation variable, the observation variable includes the accelerations of the bogie and the wheel set in the right and left direction, the filter operation means uses the state equation into which a measured value of the observation variable, the measured value of the forward-and-backward-direction force, and an actual value of the transformation variable are substituted and the observation equation into which the actual value of the transformation variable is substituted, and determines the state variables when an error between, of the observation variable, the measured value and a calculated value or an expected value of the error becomes minimum, the track state calculation means uses the angular displacement of the bogie in the yawing direction, which is one of the state variables determined by the filter operation means, and the actual value of the transformation variable to derive an estimated value of the angular displacement of the wheel set in the yawing direction, and uses the derived estimated value of the angular displacement of the wheel set in the yawing direction to derive the information reflecting the state of the track, and the actual value of the transformation variable is derived by using the measured value of the forward-and-backward-direction force.

[0009] An inspection method of the present invention includes: a data acquisition step of acquiring measured data being data of measured values to be measured by causing a railway vehicle including a vehicle body, a bogie, and a wheel set to travel on a track; a filter operation step of performing an operation using a filter performing data assimilation by using the measured data, a state equation, and an observation equation, and thereby determining state variables being variables to be determined in the state equation; and a track state calculation step of deriving information reflecting a state of the track, in which the measured data contain measured values of accelerations of the bogie and the wheel set in a right and left direction and a measured value of a forward-and-backward-direction force, the right and left direction is a direction vertical to both a forward and backward direction being a direction along a traveling direction of the railway vehicle and an up and down direction being a direction vertical to the track, the forward-and-backward-direction force is a force in the forward and backward direction to occur in a member disposed between the wheel set and the bogie on which the wheel set is provided, and is a force to be determined according to a difference between an angular displacement of the wheel set in a yawing direction and an angular displacement of the bogie on which the wheel set is provided in the yawing direction, the member is a member for supporting an axle box, the yawing direction is a pivoting direction with the up and down direction set as a pivot axis, the state equation is an equation described by using the state variables, the forward-and-backward-direction force, and a transformation variable, the state variables include a displacement and a velocity of the bogie in the right and left direction, an angular displacement and an angular velocity of the bogie in the yawing direction, an angular displacement and an angular velocity of the bogie in a rolling direction, a displacement and a velocity of the wheel set in the right and left direction, and an angular displacement of an air spring attached to the railway vehicle in the rolling direction, and do not include an angular displacement or an angular velocity of the wheel set in the yawing direction, the rolling direction is a pivoting direction with the forward and backward direction set as a pivot axis, the transformation variable is a variable that performs mutual transformation between the angular displacement of the wheel set in the yawing direction and the angular displacement of the bogie in the yawing direction, the observation equation is an equation described by using an observation variable and the transformation variable, the observation variable includes the accelerations of the bogie and the wheel set in the right and left direction, the filter operation step uses the state equation into which a measured value of the observation variable, the measured value of the forward-and-backward-direction force, and an actual value of the transformation variable are substituted and the observation equation into which the actual value of the transformation variable is substituted, and determines the state variables when an error between, of the observation variable, the measured value and a calculated value or an expected value of the error becomes minimum, the track state calculation step uses the angular displacement of the bogie in the yawing direction, which is one of the state variables determined by the filter operation step, and the actual value of the transformation variable to derive an estimated value of the angular displacement of the wheel set in the yawing direction, and uses the derived estimated value of the angular displacement of the wheel set in the yawing direction to derive the information reflecting the state of the track, and the actual value of the transformation variable is derived by using the measured value of the forward-and-backward-direction force.

[0010] A program of the present invention causes a computer to execute steps including: a data acquisition step of

acquiring measured data being data of measured values to be measured by causing a railway vehicle including a vehicle body, a bogie, and a wheel set to travel on a track; a filter operation step of performing an operation using a filter performing data assimilation by using the measured data, a state equation, and an observation equation, and thereby determining state variables being variables to be determined in the state equation; and a track state calculation step of deriving information reflecting a state of the track, in which the measured data contain measured values of accelerations of the bogie and the wheel set in a right and left direction and a measured value of a forward-and-backward-direction force, the right and left direction is a direction vertical to both a forward and backward direction being a direction along a traveling direction of the railway vehicle and an up and down direction being a direction vertical to the track, the forward-and-backward-direction force is a force in the forward and backward direction to occur in a member disposed between the wheel set and the bogie on which the wheel set is provided, and is a force to be determined according to a difference between an angular displacement of the wheel set in a yawing direction and an angular displacement of the bogie on which the wheel set is provided in the yawing direction, the member is a member for supporting an axle box, the yawing direction is a pivoting direction with the up and down direction set as a pivot axis, the state equation is an equation described by using the state variables, the forward-and-backward-direction force, and a transformation variable, the state variables include a displacement and a velocity of the bogie in the right and left direction, an angular displacement and an angular velocity of the bogie in the yawing direction, an angular displacement and an angular velocity of the bogie in a rolling direction, a displacement and a velocity of the wheel set in the right and left direction, and an angular displacement of an air spring attached to the railway vehicle in the rolling direction, and do not include an angular displacement or an angular velocity of the wheel set in the yawing direction, the rolling direction is a pivoting direction with the forward and backward direction set as a pivot axis, the transformation variable is a variable that performs mutual transformation between the angular displacement of the wheel set in the yawing direction and the angular displacement of the bogie in the yawing direction, the observation equation is an equation described by using an observation variable and the transformation variable, the observation variable includes the accelerations of the bogie and the wheel set in the right and left direction, the filter operation step uses the state equation into which a measured value of the observation variable, the measured value of the forward-and-backward-direction force, and an actual value of the transformation variable are substituted and the observation equation into which the actual value of the transformation variable is substituted, and determines the state variables when an error between, of the observation variable, the measured value and a calculated value or an expected value of the error becomes minimum, the track state calculation step uses the angular displacement of the bogie in the yawing direction, which is one of the state variables determined by the filter operation step, and the actual value of the transformation variable to derive an estimated value of the angular displacement of the wheel set in the yawing direction, and uses the derived estimated value of the angular displacement of the wheel set in the yawing direction to derive the information reflecting the state of the track, and the actual value of the transformation variable is derived by using the measured value of the forward-and-backward-direction force.

BRIEF DESCRIPTION OF DRAWINGS

[0011]

Fig. 1 is a view illustrating one example of an outline of a railway vehicle.

Fig. 2 is a view schematically illustrating directions of main motions of components of the railway vehicle.

Fig. 3 is a view illustrating one example of an alignment irregularity amount.

Fig. 4 is a view illustrating one example of interactive acting relations between the alignment irregularity amount and motions of the components of the railway vehicle.

Fig. 5 is a view illustrating one example of interactive acting relations between the alignment irregularity amount and the motions of the components of the railway vehicle by using forward-and-backward-direction forces.

Fig. 6 is a view illustrating one example of acting relations necessary for determining the motions of the components directly acting on yawings of wheel sets.

Fig. 7 is a view illustrating one example of acting relations necessary for determining the alignment irregularity amount.

Fig. 8 is a diagram illustrating one example of a functional configuration of an inspection apparatus.

Fig. 9 is a diagram illustrating one example of a hardware configuration of the inspection apparatus.

Fig. 10 is a chart illustrating one example of preprocessing in the inspection apparatus.

Fig. 11 is a chart illustrating one example of main processing in the inspection apparatus.

Fig. 12 is a view illustrating one example of observation data.

Fig. 13 is a view illustrating one example of an actual measured value and a calculated value of the alignment irregularity amount.

Fig. 14 is a view illustrating one example of a constitution of an inspection system.

DESCRIPTION OF EMBODIMENTS

[0012] Hereinafter, there will be explained embodiments of the present invention with reference to the drawings.

5 (First embodiment)

[0013] First, there will be explained a first embodiment.

[0014] Fig. 1 is a view illustrating one example of an outline of a railway vehicle. Incidentally, in Fig. 1, the railway vehicle is set to proceed in the positive direction of the x axis (the x axis is an axis along a traveling direction of the railway vehicle). Further, the z axis is set to a direction vertical to a track 16 (the ground) (a height direction of the railway vehicle). The y axis is set to a horizontal direction vertical to the traveling direction of the railway vehicle (a direction vertical to both the traveling direction and the height direction of the railway vehicle). Further, the railway vehicle is set to a commercial vehicle. Incidentally, in Fig. 1 and Fig 3, the mark of ● added inside ○ indicates the direction from the far side of the sheet toward the near side. In Fig. 1, this direction is the positive direction of the y axis. In Fig. 3, this direction is the positive direction of the z axis.

[0015] As illustrated in Fig. 1, in this embodiment, the railway vehicle includes a vehicle body 11, bogies 12a, 12b, and wheel sets 13a to 13d. As above, in this embodiment, the railway vehicle including the single vehicle body 11 provided with the two bogies 12a, 12b and four sets of the wheel sets 13a to 13d will be explained as an example. The wheel sets 13a to 13d have axles 15a to 15d and wheels 14a to 14d provided on both ends of the axles 15a to 15d respectively. In this embodiment, the case of the bogies 12a, 12b each being a bolsterless bogie will be explained as an example. Incidentally, in Fig. 1, for convenience of illustration, only the wheels 14a to 14d on one side of the wheel sets 13a to 13d are illustrated, but wheels are also provided on the other side of the wheel sets 13a to 13d (in the example illustrated in Fig. 1, there are eight wheels in total). Further, the railway vehicle includes components other than the components illustrated in Fig. 1 (components and so on to be explained in later-described motion equations), but for convenience of illustration, illustrations of these components are omitted in Fig. 1. For example, the bogies 12a, 12b have bogie frames, bolster springs, and so on. Further, an axle box is disposed on the both sides of each of the wheel sets 13a to 13d in the right and left direction. Further, the bogie frame and the axle box are coupled to each other by an axle box suspension. The axle box suspension is a device (suspension) to be disposed between the axle box and the bogie frame. The axle box suspension absorbs vibration to be conveyed to the railway vehicle from the track 16. Further, the axle box suspension supports the axle box in a state where the position of the axle box relative to the bogie frame is restricted, so as to prevent the axle box from moving in the forward and backward direction and the right and left direction relative to the bogie frame (so as to prevent these movements from occurring preferably). The axle box suspension is disposed on the both sides of each of the wheel sets 13a to 13d in the right and left direction. Incidentally, the railway vehicle itself can be fabricated by a well-known technique, and thus its detailed explanation is omitted here.

[0016] When the railway vehicle travels on the track 16, acting force (creep force) between the wheels 14a to 14d and the track 16 becomes a vibration source and the vibration sequentially propagates to the wheel sets 13a to 13d, the bogies 12a, 12b, and the vehicle body 11. Fig. 2 is a view conceptually illustrating directions of the main motions of the components (the wheel sets 13a to 13d, the bogies 12a, 12b, and the vehicle body 11) of the railway vehicle. The x axis, the y axis, and the z axis illustrated in Fig. 2 correspond to the x axis, the y axis, and the z axis illustrated in Fig. 1 respectively.

[0017] In this embodiment as illustrated in Fig. 2, there will be explained, as an example, the case where the wheel sets 13a to 13d, the bogies 12a, 12b, and the vehicle body 11 perform pivoting motion about the x axis as a pivot axis, pivoting motion about the z axis as a pivot axis, and motion in the direction along the y axis. In the following explanation, the pivoting motion about the x axis as a pivot axis is referred to as rolling as necessary, the pivoting direction about the x axis as a pivot axis is referred to as a rolling direction as necessary, and the direction along the x axis is referred to as the forward and backward direction as necessary. Incidentally, the forward and backward direction is the traveling direction of the railway vehicle. In this embodiment, the direction along the x axis is the traveling direction of the railway vehicle. Further, the pivoting motion about the z axis as a pivot axis is referred to as yawing as necessary, the pivoting direction about the z axis as a pivot axis is referred to as a yawing direction as necessary, and the direction along the z axis is referred to as the up and down direction as necessary. Incidentally, the up and down direction is a direction vertical to the track 16. Further, the motion in the direction along the y axis is referred to as a transversal vibration as necessary, and the direction along the y axis is referred to as the right and left direction as necessary. Incidentally, the right and left direction is a direction vertical to both the forward and backward direction (traveling direction of the railway vehicle) and the up and down direction (direction vertical to the track 16). Incidentally, the railway vehicle performs motions other than these, but in this embodiment, these motions are not considered in order to simplify the explanation. However, these motions may be considered.

<Motion equation>

[0018] On the premise of the above, there will be explained one example of motion equations that describe the motions when the railway vehicle travels. In this embodiment, there will be explained, as an example, the case where the railway vehicle has 21 degrees of freedom. That is, it is set that the wheel sets 13a to 13d perform the motion in the right and left direction (transversal vibration) and the motion in the yawing direction (yawing) (2×4 sets = eight degrees of freedom). Further, it is set that the bogies 12a, 12b perform the motion in the right and left direction (transversal vibration), the motion in the yawing direction (yawing), and the motion in the rolling direction (rolling) (3×2 sets = six degrees of freedom). Further, the vehicle body 11 performs the motion in the right and left direction (transversal vibration), the motion in the yawing direction (yawing), and the motion in the rolling direction (rolling) (3×1 sets = three degrees of freedom). Further, it is set that air springs (the bolster springs) each provided on the bogies 12a, 12b perform the motion in the rolling direction (rolling) (1×2 sets = two degrees of freedom). Further, it is set that yaw dampers each provided on the bogies 12a, 12b perform the motion in the yawing direction (yawing) (1×2 sets = two degrees of freedom).

[0019] Incidentally, the degree of freedom is not limited to 21 degrees of freedom. When the degree of freedom increases, calculation accuracy improves, but a calculation load becomes high. Further, there is a risk that a later-described Kalman filter no longer operates stably. It is possible to appropriately determine the degree of freedom considering these points. Further, the following motion equations can be achieved by representing actions in the respective directions (right and left direction, yawing direction, and rolling direction) of the respective components (vehicle body 11, bogies 12a, 12b, and wheel sets 13a to 13d) based on the descriptions of Non-Patent Literatures 1, 2, for example. Thus, outlines of these motion equations will be explained here, and their detailed explanations are omitted.

[0020] In each of the following equations, each subscript w indicates the wheel sets 13a to 13d. Variables to which (only) the subscript w is added indicate that they are common to the wheel sets 13a to 13d. Subscripts w1, w2, w3, and w4 indicate the wheel sets 13a, 13b, 13c, and 13d respectively.

[0021] Subscripts t, T indicate the bogies 12a, 12b. Variables to which (only) the subscripts t, T are added indicate that they are common to the bogies 12a, 12b. Subscripts t1, t2 indicate the bogies 12a, 12b respectively.

[0022] Subscripts b, B indicate the vehicle body 11.

[0023] A subscript x indicates the forward and backward direction or the rolling direction, and a subscript y indicates the right and left direction, and a subscript z indicates the up and down direction or the yawing direction.

[0024] Further, "·" and "·" each added above a variable indicate a second-order time differential and a first-order time differential respectively.

[0025] Incidentally, when the following motion equations are explained, explanations of the already-explained variables are omitted as necessary.

[Transversal vibration of the wheel set]

[0026] The motion equations that describe the transversal vibrations of the wheel sets 13a to 13d (motion in the right and left direction) are expressed by (1) Equation to (4) Equation below.

[Mathematical equation 1]

[Mathematical equation 1]

$$m_w \ddot{y}_{w1} + \frac{f_2}{v} \dot{y}_{w1} + C_{wy} [\dot{y}_{w1} - (\dot{y}_{t1} + a \dot{\psi}_{t1} + h_1 \dot{\phi}_{t1})] - f_2 \psi_{w1} + K_{wy} [y_{w1} - \{y_{t1} + a \psi_{t1} + h_1 \phi_{t1}\}] = 0$$

$$\dots (1)$$

$$m_w \ddot{y}_{w2} + \frac{f_2}{v} \dot{y}_{w2} + C_{wy} [\dot{y}_{w2} - (\dot{y}_{t1} + a \dot{\psi}_{t1} + h_1 \dot{\phi}_{t1})] - f_2 \psi_{w2} + K_{wy} [y_{w2} - \{y_{t1} + a \psi_{t1} + h_1 \phi_{t1}\}] = 0$$

$$\dots (2)$$

$$m_w \ddot{y}_{w3} + \frac{f_2}{v} \dot{y}_{w3} + C_{wy} [\dot{y}_{w3} - (\dot{y}_{t2} + a \dot{\psi}_{t2} + h_1 \dot{\phi}_{t2})] - f_2 \psi_{w3} + K_{wy} [y_{w3} - \{y_{t2} + a \psi_{t2} + h_1 \phi_{t2}\}] = 0$$

$$\dots (3)$$

$$m_w \ddot{y}_{w1} + \frac{f_2}{v} \dot{y}_{w1} + C_{wy} [\dot{y}_{w1} - (\dot{y}_{t2} + a \dot{\psi}_{t2} + h_1 \dot{\phi}_{t2})] - f_2 \psi_{w1} + K_{wy} [y_{w1} - (y_{t2} + a \psi_{t2} + h_1 \phi_{t2})] = 0 \quad \dots (4)$$

[0027] m_w is the mass of the wheel sets 13a to 13d. $y_{w1} \ddot{}$ is acceleration of the wheel set 13a in the right and left direction (in the equation, $\ddot{}$ is added above y_{w1} (the same is true of the other variables below)). f_2 is a lateral creep coefficient. v is a traveling velocity of the railway vehicle. $y_{w1} \dot{}$ is a velocity of the wheel set 13a in the right and left direction (in the equation, $\dot{}$ is added above y_{w1} (the same is true of the other variables below)). C_{wy} is a damping constant of the axle box suspension coupling the axle box and the wheel set in the right and left direction. $y_{t1} \dot{}$ is a velocity of the bogie 12a in the right and left direction. a represents 1/2 of each distance between the wheel sets 13a and 13b and between the wheel sets 13c and 13d in the forward and backward direction, which are provided on the bogies 12a, 12b (the distance between the wheel sets 13a and 13b and the distance between the wheel sets 13c and 13d, which are provided on the bogies 12a, 12b, each become $2a$). $\phi_{t1} \dot{}$ is an angular velocity of the bogie 12a in the yawing direction. h_1 is a distance between the middle of the axle and the center of gravity of the bogie 12a in the up and down direction. $\phi_{t1} \dot{}$ is an angular velocity of the bogie 12a in the rolling direction. ϕ_{w1} is a pivot amount (angular displacement) of the wheel set 13a in the yawing direction. K_{wy} is a spring constant of the axle box suspension in the right and left direction. y_{w1} is a displacement of the wheel set 13a in the right and left direction. y_{t1} is a displacement of the bogie 12a in the right and left direction. ϕ_{t1} is a pivot amount (angular displacement) of the bogie 12a in the yawing direction. ϕ_{t1} is a pivot amount (angular displacement) of the bogie 12a in the rolling direction. Incidentally, respective variables in (2) Equation to (4) Equation are represented by being replaced with the variables in (1) Equation according to the meanings of the aforementioned subscripts.

[Yawing of the wheel set]

[0028] The motion equations that describe the yawings of the wheel sets 13a to 13d are expressed by (5) Equation to (8) Equation below.

[Mathematical equation 2]

[Mathematical equation 2]

$$I_{wz} \ddot{\psi}_{w1} + \frac{f_1 b^2}{v} \dot{\psi}_{w1} + C_{wx} b_1^2 \{ \dot{\psi}_{w1} - \dot{\psi}_{t1} \} + \frac{f_1 b \gamma}{r} \{ y_{w1} - y_{R1} \} + s_a K_{wy} \{ y_{w1} - y_{t1} \} + s_a C_{wy} \{ \dot{y}_{w1} - \dot{y}_{t1} \} + K_{wx} b_1^2 \{ \psi_{w1} - \psi_{t1} \} = 0 \quad \dots (5)$$

$$I_{wz} \ddot{\psi}_{w2} + \frac{f_1 b^2}{v} \dot{\psi}_{w2} + C_{wx} b_1^2 \{ \dot{\psi}_{w2} - \dot{\psi}_{t1} \} + \frac{f_1 b \gamma}{r} \{ y_{w2} - y_{R2} \} + s_a K_{wy} \{ y_{w2} - y_{t1} \} + s_a C_{wy} \{ \dot{y}_{w2} - \dot{y}_{t1} \} + K_{wx} b_1^2 \{ \psi_{w2} - \psi_{t1} \} = 0 \quad \dots (6)$$

$$I_{wz} \ddot{\psi}_{w3} + \frac{f_1 b^2}{v} \dot{\psi}_{w3} + C_{wx} b_1^2 \{ \dot{\psi}_{w3} - \dot{\psi}_{t2} \} + \frac{f_1 b \gamma}{r} \{ y_{w3} - y_{R3} \} + s_a K_{wy} \{ y_{w3} - y_{t2} \} + s_a C_{wy} \{ \dot{y}_{w3} - \dot{y}_{t2} \} + K_{wx} b_1^2 \{ \psi_{w3} - \psi_{t2} \} = 0 \quad \dots (7)$$

$$I_{wz} \ddot{\psi}_{w4} + \frac{f_1 b^2}{v} \dot{\psi}_{w4} + C_{wx} b_1^2 \{ \dot{\psi}_{w4} - \dot{\psi}_{t2} \} + \frac{f_1 b \gamma}{r} \{ y_{w4} - y_{R4} \} + s_a K_{wy} \{ y_{w4} - y_{t2} \} + s_a C_{wy} \{ \dot{y}_{w4} - \dot{y}_{t2} \} + K_{wx} b_1^2 \{ \psi_{w4} - \psi_{t2} \} = 0 \quad \dots (8)$$

[0029] I_{wz} is a moment of inertia of the wheel sets 13a to 13d in the yawing direction. $\phi_{w1} \cdot \cdot$ is angular acceleration of the wheel set 13a in the yawing direction. f_1 is a longitudinal creep coefficient. b is a distance in the right and left direction between contacts between the two wheels, which are attached to each of the wheel sets 13a to 13d, and the track 16 (rail). $\phi_{w1} \cdot$ is an angular velocity of the wheel set 13a in the yawing direction. C_{wx} is a damping constant of the axle box suspension in the forward and backward direction. b_1 represents 1/2 of the interval between the axle box suspensions in the right and left direction (the interval of the two axle box suspensions, which are provided on the right and left sides of the single wheel set, in the right and left direction becomes $2b_1$). γ is a tread slope. r is a radius of the wheels 14a to 14d. y_{R1} is an alignment irregularity amount at the position of the wheel set 13a. s_a is an offset from the middle of the axles 15a to 15d to an axle box suspension spring in the forward and backward direction. y_{t1} is a displacement of the bogie 12a in the right and left direction. K_{wx} is a spring constant of the axle box suspension in the forward and backward direction. Incidentally, respective variables in (6) Equation to (8) Equation are represented by being replaced with the variables in (5) Equation according to the meanings of the aforementioned subscripts. However, y_{R2} , y_{R3} , and y_{R4} are alignment irregularity amounts at the positions of the wheel sets 13b, 13c, and 13d respectively. Here, the alignment irregularity is a lateral displacement of a rail in a longitudinal direction as described in Japan Industrial Standard (JIS E 1001: 2001). The alignment irregularity amount is an amount of the displacement. Fig. 3 illustrates one example of the alignment irregularity amount y_{R1} at the position of the wheel set 13a. In Fig. 3, the case of the track 16 being a linear track will be explained as an example. In Fig. 3, 16a denotes a rail and 16b denotes a cross tie. In Fig. 3, it is set that the wheel 14a of the wheel set 13a is in contact with the rail 16a at a position 301. The "position of the wheel set 13a" in the alignment irregularity amount y_{R1} at the position of the wheel set 13a is a contact position between the wheel 14a of the wheel set 13a and the rail 16a. The alignment irregularity amount y_{R1} at the position of the wheel set 13a is a distance in the right and left direction between the contact position between the wheel 14a of the wheel set 13a and the rail 16a and the position of the rail 16a in the case where this position is assumed as a regular state. The alignment irregularity amounts y_{R2} , y_{R3} , and y_{R4} at the positions of the wheel sets 13b, 13c, and 13d are also defined in the same manner as the alignment irregularity amount y_{R1} at the position of the wheel set 13a.

[Transversal vibration of the bogie]

[0030] The motion equations that describe the transversal vibrations of the bogies 12a, 12b (motion in the right and left direction) are expressed by (9) Equation and (10) Equation below.

[Mathematical equation 3]

[Mathematical equation 3]

$$m_T \ddot{y}_{t1} + c'_2 [\{\dot{y}_{t1} - h_4 \dot{\phi}_{t1}\} - \{\dot{y}_b + L \dot{\psi}_b + h_5 \dot{\phi}_b\}] + 2C_{wy} \{\dot{y}_{t1} + h_1 \dot{\phi}_{t1}\} - C_{wy} \{\dot{y}_{w1} + \dot{y}_{w2}\} \\ + 2k'_2 [\{y_{t1} - h_2 \phi_{t1}\} - \{y_b + L \psi_b + h_3 \phi_b\}] + 2K_{wy} \{y_{t1} + h_1 \phi_{t1}\} - K_{wy} \{y_{w1} + y_{w2}\} = 0 \\ \dots (9)$$

$$m_T \ddot{y}_{t2} + c'_2 [\{\dot{y}_{t2} - h_4 \dot{\phi}_{t2}\} - \{\dot{y}_b + L \dot{\psi}_b + h_5 \dot{\phi}_b\}] + 2C_{wy} \{\dot{y}_{t1} + h_1 \dot{\phi}_{t1}\} - C_{wy} \{\dot{y}_{w3} + \dot{y}_{w4}\} \\ + 2k'_2 [\{y_{t2} - h_2 \phi_{t2}\} - \{y_b + L \psi_b + h_3 \phi_b\}] + 2K_{wy} \{y_{t2} + h_1 \phi_{t2}\} - K_{wy} \{y_{w3} + y_{w4}\} = 0 \\ \dots (10)$$

[0031] m_T is the mass of the bogies 12a, 12b. $y_{t1} \cdot \cdot$ is acceleration of the bogie 12a in the right and left direction. c'_2 is a damping constant of a lateral movement damper. h_4 is a distance between the center of gravity of the bogie 12a and the lateral movement damper in the up and down direction. $y_b \cdot$ is a velocity of the vehicle body 11 in the right and left direction. L represents 1/2 of the interval between the center of the bogie 12a and the center of the bogie 12b in the forward and backward direction (the interval between the center of the bogie 12a and the center of the bogie 12b in the forward and backward direction becomes $2L$). $\phi_b \cdot$ is an angular velocity of the vehicle body 11 in the yawing direction. h_5 is a distance between the lateral movement damper and the center of gravity of the vehicle body 11 in the up and down direction. $\phi_b \cdot$ is an angular velocity of the vehicle body 11 in the rolling direction. $y_{w2} \cdot$ is a velocity of the wheel set 13b in the right and left direction. k'_2 is a spring constant of the air spring (bolster spring) in the right and left direction. h_2 is a distance between the center of gravity of each of the bogies 12a, 12b and the center of the air spring (bolster spring) in the up and down direction. y_b is a displacement of the vehicle body 11 in the right and left direction. ϕ_b is a pivot amount (angular displacement) of the vehicle body 11 in the yawing direction. h_3 is a distance between the center

of the air spring (bolster spring) and the center of gravity of the vehicle body 11 in the up and down direction. ϕ_b is a pivot amount (angular displacement) of the vehicle body 11 in the rolling direction. Incidentally, respective variables in (10) Equation are represented by being replaced with the variables in (9) Equation according to the meanings of the aforementioned subscripts.

[Yawing of the bogie]

[0032] The motion equations that describe the yawings of the bogies 12a, 12b are expressed by (11) Equation and (12) Equation below.

[Mathematical equation 4]

[Mathematical equation 4]

$$\begin{aligned} I_{Tz} \ddot{\psi}_{t1} + C_{wx} b_1^2 \{ \dot{\psi}_{t1} - \dot{\psi}_{w1} \} + C_{wx} b_1^2 \{ \dot{\psi}_{t1} - \dot{\psi}_{w2} \} + 2C_{wy} a^2 \dot{\psi}_{t1} - C_{wy} a \{ \dot{y}_{w1} - \dot{y}_{w2} \} \\ + K_{wx} b_1^2 \{ \psi_{t1} - \psi_{w1} \} + K_{wx} b_1^2 \{ \psi_{t1} - \psi_{w2} \} + 2K_{wy} a^2 \psi_{t1} - K_{wy} a \{ y_{w1} - y_{w2} \} \\ + 2k'_0 (b'_0)^2 \{ \psi_{t1} - \psi_{y1} \} + 2k''_2 b_2^2 \{ \psi_{t1} - \psi_b \} = 0 \end{aligned} \quad \dots (11)$$

$$\begin{aligned} I_{Tz} \ddot{\psi}_{t2} + C_{wx} b_1^2 \{ \dot{\psi}_{t2} - \dot{\psi}_{w3} \} + C_{wx} b_1^2 \{ \dot{\psi}_{t2} - \dot{\psi}_{w4} \} + 2C_{wy} a^2 \dot{\psi}_{t2} - C_{wy} a \{ \dot{y}_{w3} - \dot{y}_{w4} \} \\ + K_{wx} b_1^2 \{ \psi_{t2} - \psi_{w3} \} + K_{wx} b_1^2 \{ \psi_{t2} - \psi_{w4} \} + 2K_{wy} a^2 \psi_{t2} - K_{wy} a \{ y_{w3} - y_{w4} \} \\ + 2k'_0 (b'_0)^2 \{ \psi_{t2} - \psi_{y2} \} + 2k''_2 b_2^2 \{ \psi_{t2} - \psi_b \} = 0 \end{aligned} \quad \dots (12)$$

[0033] I_{Tz} is a moment of inertia of the bogies 12a, 12b in the yawing direction. ϕ_{t1} is angular acceleration of the bogie 12a in the yawing direction. ϕ_{w2} is an angular velocity of the wheel set 13b in the yawing direction. ϕ_{w2} is a pivot amount (angular displacement) of the wheel set 13b in the yawing direction. y_{w2} is a displacement of the wheel set 13b in the right and left direction. k'_0 is stiffness of a rubber bush of the yaw damper. b'_0 represents 1/2 of the interval between the two yaw dampers, which are disposed on the right and left sides of each of the bogies 12a, 12b, in the right and left direction (the interval between the two yaw dampers, which are disposed on the right and left sides of each of the bogies 12a, 12b, in the right and left direction becomes $2b'_0$). ϕ_{y1} is a pivot amount (angular displacement) of the yaw damper disposed on the bogie 12a in the yawing direction. k''_2 is a spring constant of the air spring (bolster spring) in the right and left direction. b_2 represents 1/2 of the interval between the two air springs (bolster springs), which are disposed on the right and left sides of each of the bogies 12a, 12b, in the right and left direction (the interval between the two air springs (bolster springs), which are disposed on the right and left sides of each of the bogies 12a, 12b, in the right and left direction becomes $2b_2$). Incidentally, respective variables in (12) Equation are represented by being replaced with the variables in (11) Equation according to the meanings of the aforementioned subscripts.

[Rolling of the bogie]

[0034] The motion equations that describe the rollings of the bogies 12a, 12b are expressed by (13) Equation and (14) Equation below.

[Mathematical equation 5]

[Mathematical equation 5]

$$\begin{aligned}
& I_{Tx} \ddot{\phi}_{t1} \\
& + 2 c_1 (b'_1)^2 \dot{\phi}_{t1} + 2 c_2 b_2^2 \{ \dot{\phi}_{t1} - \dot{\phi}_{a1} \} + C_{wy} h_1 [2 \{ \dot{y}_{t1} + h_1 \dot{\phi}_{t1} \} - \{ \dot{y}_{w1} + \dot{y}_{w2} \}] \\
& - c'_2 h_4 [\{ \dot{y}_{t1} - h_4 \dot{\phi}_{t1} \} - \{ \dot{y}_b + L \dot{\psi}_b + h_5 \dot{\phi}_b \}] \\
& + 2 k_1 b_1^2 \phi_{t1} + 2 \lambda k_2 b_2^2 \{ \phi_{t1} - \phi_{a1} \} + K_{wy} h_1 [2 \{ y_{t1} + h_1 \phi_{t1} \} - \{ y_{w1} + y_{w2} \}] \\
& - 2 k'_2 h_2 [\{ y_{t1} - h_2 \phi_{t1} \} - \{ y_b + L \psi_b + h_3 \phi_b \}] \\
& + 2 k_3 b_2^2 \{ \phi_{t1} - \phi_b \} = 0 \quad \dots (13)
\end{aligned}$$

$$\begin{aligned}
& I_{Tx} \ddot{\phi}_{t2} \\
& + 2 c_1 (b'_1)^2 \dot{\phi}_{t2} + 2 c_2 b_2^2 \{ \dot{\phi}_{t2} - \dot{\phi}_{a2} \} + C_{wy} h_1 [2 \{ \dot{y}_{t2} + h_1 \dot{\phi}_{t2} \} - \{ \dot{y}_{w3} + \dot{y}_{w4} \}] \\
& - c'_2 h_4 [\{ \dot{y}_{t2} - h_4 \dot{\phi}_{t2} \} - \{ \dot{y}_b - L \dot{\psi}_b + h_5 \dot{\phi}_b \}] \\
& + 2 k_1 b_1^2 \phi_{t2} + 2 \lambda k_2 b_2^2 \{ \phi_{t2} - \phi_{a2} \} + K_{wy} h_1 [2 \{ y_{t2} + h_1 \phi_{t2} \} - \{ y_{w3} + y_{w4} \}] \\
& - 2 k'_2 h_2 [\{ y_{t2} - h_2 \phi_{t2} \} - \{ y_b + L \psi_b + h_3 \phi_b \}] \\
& + 2 k_3 b_2^2 \{ \phi_{t2} - \phi_b \} = 0 \quad \dots (14)
\end{aligned}$$

[0035] I_{Tx} is a moment of inertia of the bogies 12a, 12b in the rolling direction. ϕ_{t1} is angular acceleration of the bogie 12a in the rolling direction. c_1 is a damping constant of an axle damper in the up and down direction. b'_1 represents 1/2 of the interval between the two axle dampers, which are disposed on the right and left sides of each of the bogies 12a, 12b, in the right and left direction (the interval between the two axle dampers, which are disposed on the right and left sides of each of the bogies 12a, 12b, in the right and left direction becomes $2b'_1$). c_2 is a damping constant of the air spring (bolster spring) in the up and down direction. ϕ_{a1} is an angular velocity of the air spring (bolster spring) disposed on the bogie 12a in the rolling direction. k_1 is a spring constant of an axle spring in the up and down direction. λ is a value obtained by dividing the volume of the air spring (bolster spring) main body by the volume of an auxiliary air chamber. k_2 is a spring constant of the air spring (bolster spring) in the up and down direction. ϕ_{a1} is a pivot amount (angular displacement) of the air spring (bolster spring) disposed on the bogie 12a in the rolling direction. k_3 is equivalent stiffness by a change in effective pressure receiving area of the air spring (bolster spring). Incidentally, respective variables in (14) Equation are represented by being replaced with the variables in (13) Equation according to the meanings of the aforementioned subscripts. However, ϕ_{a2} is a pivot amount (angular displacement) of the air spring (bolster spring) disposed on the bogie 12b in the rolling direction.

[Transversal vibration of the vehicle body]

[0036] The motion equation that describes the transversal vibration of the vehicle body 11 (motion in the right and left direction) is expressed by (15) Equation below.

[Mathematical equation 6]

[Mathematical equation 6]

$$\begin{aligned}
& m_B \ddot{y}_b + 2c'_2 \{ \dot{y}_b + h_5 \dot{\phi}_b \} - c'_2 [\{ \dot{y}_{t1} + \dot{y}_{t2} \} - h_4 \{ \dot{\phi}_{t1} + \dot{\phi}_{t2} \}] \\
& + 4k'_2 \{ y_b + h_3 \phi_b \} - 2k'_2 [\{ y_{t1} + y_{t2} \} - h_2 \{ \phi_{t1} + \phi_{t2} \}] = 0 \quad \dots (15)
\end{aligned}$$

[0037] m_B is the mass of the bogies 12a, 12b. y_b is acceleration of the vehicle body 11 in the right and left direction. $\dot{y}_{t2}$ is a velocity of the bogie 12b in the right and left direction. $\dot{\phi}_{t2}$ is an angular velocity of the bogie 12b in the rolling direction. y_{t2} is a displacement of the bogie 12b in the right and left direction. ϕ_{t2} is a pivot amount (angular displacement) of the bogie 12b in the rolling direction.

[Yawing of the vehicle body]

[0038] The motion equation that describes the yawing of the vehicle body 11 is expressed by (16) Equation below.
[Mathematical equation 7]
[Mathematical equation 7]

$$\begin{aligned}
& I_{Bz} \ddot{\psi}_b + 2c'_2 L^2 \dot{\psi}_b - c'_2 L \{ \dot{y}_{t1} - \dot{y}_{t2} \} + c'_2 L h_4 \{ \dot{\phi}_{t1} - \dot{\phi}_{t2} \} \\
& + 2c_0 (b'_0)^2 \{ \dot{\psi}_b - \dot{\psi}_{y1} \} + 2c_0 (b'_0)^2 \{ \dot{\psi}_b - \dot{\psi}_{y2} \} \\
& + 4k'_2 L^2 \psi_b - 2k'_2 L \{ y_{t1} - y_{t2} \} + 2k'_2 L h_2 \{ \phi_{t1} - \phi_{t2} \} \\
& + 2k''_2 b_2^2 \{ \psi_b - \psi_{t1} \} + 2k''_2 b_2^2 \{ \psi_b - \psi_{t2} \} = 0 \quad \dots (16)
\end{aligned}$$

[0039] I_{Bz} is a moment of inertia of the vehicle body 11 in the yawing direction. $\dot{\phi}_b$ is angular acceleration of the vehicle body 11 in the yawing direction. c_0 is a damping constant of the yaw damper in the forward and backward direction. $\dot{\phi}_{y1}$ is an angular velocity of the yaw damper disposed on the bogie 12a in the yawing direction. $\dot{\phi}_{y2}$ is an angular velocity of the yaw damper disposed on the bogie 12b in the yawing direction. ϕ_{t2} is a pivot amount (angular displacement) of the bogie 12b in the yawing direction.

[Rolling of the vehicle body]

[0040] The motion equation that describes the rolling of the vehicle body 11 is expressed by (17) Equation below.
[Mathematical equation 8]
[Mathematical equation 8]

$$\begin{aligned}
& I_{Bx} \ddot{\phi}_b + 2c'_2 h_5 \{ \dot{y}_b + h_5 \dot{\phi}_b \} - c'_2 h_5 [\{ \dot{y}_{t1} + \dot{y}_{t2} \} - h_4 \{ \dot{\phi}_{t1} + \dot{\phi}_{t2} \}] \\
& + 4k'_2 h_3 \{ y_b + h_3 \phi_b \} - 2k'_2 h_3 [\{ y_{t1} + y_{t2} \} - h_2 \{ \phi_{t1} + \phi_{t2} \}] \\
& + 2k_3 b_2^2 \{ \phi_b - \phi_{t1} \} + 2k_3 b_2^2 \{ \phi_b - \phi_{t2} \} \\
& + 2k_2 b_2^2 \{ \phi_b - \phi_{a1} \} + 2k_2 b_2^2 \{ \phi_b - \phi_{a2} \} = 0 \quad \dots (17)
\end{aligned}$$

[0041] I_{Bx} is a moment of inertia of the vehicle body 11 in the rolling direction. $\dot{\phi}_b$ is angular acceleration of the vehicle body 11 in the rolling direction.

[Yawing of the damper]

[0042] The motion equations that describe the yawing of the yaw damper disposed on the bogie 12a and the yawing of the yaw damper disposed on the bogie 12b are expressed by (18) Equation and (19) Equation below respectively.

[Mathematical equation 9]

[Mathematical equation 9]

$$2 c_0 (b'_0)^2 \{ \dot{\psi}_{y1} - \dot{\psi}_b \} + 2 k'_0 (b'_0)^2 \{ \psi_{y1} - \psi_{t1} \} = 0 \quad \cdot \cdot \cdot \quad (18)$$

$$2 c_0 (b'_0)^2 \{ \dot{\psi}_{y2} - \dot{\psi}_b \} + 2 k'_0 (b'_0)^2 \{ \psi_{y2} - \psi_{t2} \} = 0 \quad \cdot \cdot \cdot \quad (19)$$

[0043] ϕ_{y2} is a pivot amount (angular displacement) of the yaw damper disposed on the bogie 12b in the yawing direction.

[Rolling of the air spring (bolster spring)]

[0044] The motion equations that describe the rolling of the air spring (bolster spring) disposed on the bogie 12a and the rolling of the air spring (bolster spring) disposed on the bogie 12b are expressed by (20) Equation and (21) Equation below respectively.

[Mathematical equation 10]

[Mathematical equation 10]

$$2 c_2 b_2^2 \{ \dot{\phi}_{a1} - \dot{\phi}_{t1} \} + 2 \lambda k_2 b_2^2 \{ \phi_{a1} - \phi_{t1} \} + 2 k_2 b_2^2 \{ \phi_{a1} - \phi_b \} = 0 \quad \cdot \cdot \cdot \quad (20)$$

$$2 c_2 b_2^2 \{ \dot{\phi}_{a2} - \dot{\phi}_{t2} \} + 2 \lambda k_2 b_2^2 \{ \phi_{a2} - \phi_{t2} \} + 2 k_2 b_2^2 \{ \phi_{a2} - \phi_b \} = 0 \quad \cdot \cdot \cdot \quad (21)$$

[0045] ϕ_{a2} is an angular velocity of the air spring (bolster spring) disposed on the bogie 12b in the rolling direction.

<Relations between the alignment irregularity amount of the track and the motions of the railway vehicle>

[0046] Fig. 4 is a view illustrating one example of interactive acting relations between the alignment irregularity amount and the motions of the components of the railway vehicle. Arrows drawn by a solid line indicate an acting relation between different motions of the same component. Arrows drawn by line types other than the solid line indicate an acting relation between motions of the different components. To each motion, a number of a motion equation that describes its motion, which is explained in this embodiment, is added. For example, the yawings of the wheel sets 13a to 13d are described by (5) Equation to (8) Equation. The yawings of the wheel sets 13a to 13d directly receive actions from the alignment irregularity amounts y_{R1} to y_{R4} , the transversal vibrations of the wheel sets 13a to 13d, the transversal vibrations of the bogies 12a, 12b, and the yawings of the bogies 12a, 12b. The transversal vibrations of the bogies 12a, 12b are described by (9) Equation to (10) Equation. The transversal vibrations of the bogies 12a, 12b directly receive actions from the transversal vibrations of the wheel sets 13a to 13d, the rollings of the bogies 12a, 12b, the transversal vibration of the vehicle body 11, the yawing of the vehicle body 11, the yawings of the bogies 12a, 12b, and the rolling of the vehicle body 11, and do not directly receive actions from the yawings of the wheel sets 13a to 13d.

[0047] As is clear from Fig. 4, the alignment irregularity amounts y_{R1} to y_{R4} directly act on the yawings of the wheel sets 13a to 13d. This action propagates into the motions of the other components. A state equation is created from the motion equations relating to the motions of the components that directly or indirectly receive the action from the alignment irregularity amounts y_{R1} to y_{R4} . Further, measurable state variables are measured from among the motions relating to the alignment irregularity amounts y_{R1} to y_{R4} to set an observation equation. Then, an operation using a filter that performs data assimilation such as a Kalman filter is performed, thereby making it possible to calculate the alignment irregularity amounts y_{R1} to y_{R4} . However, the degree of freedom of the motion is large in this method, and thus there is

a risk that the operation of the filter becomes no longer stable.

[0048] Thus, in order to improve the accuracy of the alignment irregularity amounts y_{R1} to y_{R4} , the present inventors thought that it is only necessary to accurately calculate the yawings of the wheel sets 13a to 13d on which the alignment irregularity amounts y_{R1} to y_{R4} directly act and factors that directly act on the yawings of the wheel sets 13a to 13d (including the motions of the components), and to calculate the alignment irregularity amounts y_{R1} to y_{R4} by using the motion equations that describe the yawings of the wheel sets 13a to 13d. Further, the creep force is decomposed into a longitudinal creep force being a component in the forward and backward direction and a lateral creep force being a component in the right and left direction. The present inventors found out that the longitudinal creep force has a high correlation with the alignment irregularity amounts y_{R1} to y_{R4} . The longitudinal creep force is measured by force in the forward and backward direction to occur in a member disposed between the wheel sets 13a to 13b (13c to 13d) and the bogie 12a (12b) on which these wheel sets 13a to 13b (13c to 13d) are provided. The force in the forward and backward direction to occur in the member is referred to as a forward-and-backward-direction force. From the above, the inventors devised a method of calculating the alignment irregularity amounts y_{R1} to y_{R4} by using a measured value of the forward-and-backward-direction force.

[0049] Further, in-phase components of the longitudinal creep force in one wheel of right and left wheels in one wheel set and the longitudinal creep force in the other wheel are components corresponding to a braking force and a driving force. Accordingly, in order to calculate the alignment irregularity amounts y_{R1} to y_{R4} even when the railway vehicle accelerates or decelerates, the forward-and-backward-direction force is preferably determined so as to correspond to an opposite-phase component of the longitudinal creep force. The opposite-phase component of the longitudinal creep force is a component to be opposite in phase to each other between the longitudinal creep force in one wheel of the right and left wheels in one wheel set and the longitudinal creep force in the other wheel. That is, the opposite-phase component of the longitudinal creep force is a component, of the longitudinal creep force, in the direction in which the axle is twisted. In this case, the forward-and-backward-direction force becomes a component opposite in phase to each other out of forward-and-backward-direction components of forces to occur in two members attached to both the right and left sides of one wheel set.

[0050] Hereinafter, there will be explained concrete examples of the forward-and-backward-direction force in the case where the forward-and-backward-direction force is determined so as to correspond to the opposite-phase component of the longitudinal creep force.

[0051] In the case of the axle box suspension being a mono-link type axle box suspension, the axle box suspension includes a link, and the axle box and the bogie frame are coupled by the link. A rubber bush is attached to both ends of the link. In this case, the forward-and-backward-direction force becomes, out of forward-and-backward-direction components of loads that two links, which are attached to right and left ends of one wheel set one by one, receive, the component to be opposite in phase to each other. Further, due to arrangement and constitution of the links, the link mainly receives, out of loads in the forward and backward direction, the right and left direction, and the forward and backward direction, the load in the forward and backward direction. Accordingly, one strain gauge only needs to be attached to each link, for example. By using a measured value of the strain gauge, the forward-and-backward-direction component of the load that this link receives is derived, to thereby obtain a measured value of the forward-and-backward-direction force. Further, in place of applying such a design, a forward-and-backward-direction displacement of the rubber bush attached to the link may be measured by a displacement meter. In this case, the product of a measured displacement and a spring constant of this rubber bush is set as the measured value of the forward-and-backward-direction force. In the case of the axle box suspension being the mono-link type axle box suspension, the previously-described member for supporting the axle box becomes the link or the rubber bush.

[0052] Incidentally, in the load measured by the strain gauge attached to the link, not only the component in the forward and backward direction, but also at least one component of a component in the right and left direction and a component in the up and down direction is sometimes contained. However, even in such a case, due to the structure of the axle box suspension, the load of the component in the right and left direction and the load of the component in the up and down direction that the link receives are sufficiently smaller than the load of the component in the forward and backward direction. Accordingly, only attaching one strain gauge to each link makes it possible to obtain a measured value of the forward-and-backward-direction force, which has accuracy to be required practically. In this manner, the components other than the component in the forward and backward direction are sometimes contained in the measured forward-and-backward-direction force, and three or more strain gauges may be attached to each link so as to cancel the strains in the up and down direction and the right and left direction. This makes it possible to improve the accuracy of the measured value of the forward-and-backward-direction force.

[0053] In the case of the axle box suspension being an axle beam type axle box suspension, the axle box suspension includes an axle beam, and the axle box and the bogie frame are coupled by the axle beam. The axle beam may be formed integrally with the axle box. A rubber bush is attached to a bogie frame-side end of the axle beam. In this case, the forward-and-backward-direction force becomes, out of forward-and-backward-direction components of loads that two axle beams, which are attached to right and left ends of one wheel set one by one, receive, the component to be

opposite in phase to each other. Further, due to arrangement and constitution of the axle beams, the axle beam is likely to receive, out of loads in the forward and backward direction, the right and left direction, and the up and down direction, the load in the right and left direction, in addition to the load in the forward and backward direction. Accordingly, two or more strain gauges are attached to each axle beam so as to cancel the strain in the right and left direction, for example.

By using measured values of these strain gauges, the forward-and-backward-direction component of the load that the axle beam receives is derived, to thereby obtain a measured value of the forward-and-backward-direction force. Further, in place of applying such a design, a forward-and-backward-direction displacement of the rubber bush attached to the axle beam may be measured by a displacement meter. In this case, the product of a measured displacement and a spring constant of this rubber bush is set as the measured value of the forward-and-backward-direction force. In the case of the axle box suspension being the axle beam type axle box suspension, the previously-described member for supporting the axle box becomes the axle beam or the rubber bush.

[0054] Incidentally, in the load measured by the strain gauge attached to the axle beam, not only the components in the forward and backward direction and the right and left direction, but also the component in the up and down direction is sometimes contained. However, even in such a case, due to the structure of the axle box suspension, the load of the component in the up and down direction that the axle beam receives is sufficiently smaller than the load of the component in the forward and backward direction and the load of the component in the right and left direction. Accordingly, unless the strain gauge is attached so as to cancel the load of the component in the up and down direction that the axle beam receives, a measured value of the forward-and-backward-direction force, which has accuracy to be required practically, can be obtained. In this manner, the components other than the component in the forward and backward direction are sometimes contained in the measured forward-and-backward-direction force, and three or more strain gauges may be attached to each axle beam so as to cancel the strain in the up and down direction as well as the strain in the right and left direction. This makes it possible to improve the accuracy of the measured value of the forward-and-backward-direction force.

[0055] In the case of the axle box suspension being a leaf spring type axle box suspension, the axle box suspension includes a leaf spring, and the axle box and the bogie frame are coupled by the leaf spring. A rubber bush is attached to ends of the leaf spring. In this case, the forward-and-backward-direction force becomes, out of forward-and-backward-direction components of loads that two leaf springs, which are attached to right and left ends of one wheel set one by one, receive, the component to be opposite in phase to each other. Further, due to arrangement and constitution of the leaf springs, the leaf spring is likely to receive, out of loads in the forward and backward direction, the right and left direction, and the up and down direction, the load in the right and left direction and the load in the up and down direction, in addition to the load in the forward and backward direction. Accordingly, three or more strain gauges are attached to each leaf spring so as to cancel the strains in the right and left direction and the up and down direction, for example. By using measured values of these strain gauges, the forward-and-backward-direction component of the load that the leaf spring receives is derived, to thereby obtain a measured value of the forward-and-backward-direction force. Further, in place of applying such a design, a forward-and-backward-direction displacement of the rubber bush attached to the leaf spring may be measured by a displacement meter. In this case, the product of a measured displacement and a spring constant of this rubber bush is set as the measured value of the forward-and-backward-direction force. In the case of the axle box suspension being the leaf spring type axle box suspension, the previously-described member for supporting the axle box becomes the leaf spring or the rubber bush.

[0056] Incidentally, as the aforementioned displacement meter, a well-known laser displacement meter or eddy current displacement meter can be used.

[0057] Further, the forward-and-backward-direction force was explained here by taking the case of the system of the axle box suspension being a mono-link type, an axle beam type, and a leaf spring type as an example. However, the system of the axle box suspension is not limited to the mono-link type, the axle beam type, and the leaf spring type. In conformity with the system of the axle box suspension, the forward-and-backward-direction force can be determined in the same manner as in the mono-link type, the axle beam type, and the leaf spring type.

[0058] Further, the case where a measured value of a single forward-and-backward-direction force can be obtained in one wheel set will be explained as an example, in order to simplify the explanation below. That is, the railway vehicle illustrated in Fig. 1 has the four wheel sets 13a to 13d. Accordingly, it is possible to obtain measured values of four forward-and-backward-direction forces T_1 to T_4 .

[0059] Fig. 5 is a view that illustrates one example of interactive acting relations between the alignment irregularity amounts y_{R1} to y_{R4} and the motions of the components of the railway vehicle while using the forward-and-backward-direction forces T_1 to T_4 . There will be later explained concrete examples of calculation equations of the forward-and-backward-direction forces T_1 to T_4 , calculation equations of transformation variables e_1 to e_4 , motion equations that describe transversal vibrations of the wheel sets 13a to 13d when the transformation variables e_1 to e_4 are used, and motion equations that describe yawings of the wheel sets 13a to 13d when the forward-and-backward-direction forces T_1 to T_4 are used (refer to (40) Equation to (43) Equation, (26) Equation to (29) Equation, (34) Equation to (37) Equation, and (51) Equation to (54) Equation respectively).

[0060] Fig. 6 is a view illustrating acting relations necessary for determining the motions of the components that directly act on the yawings of the wheel sets 13a to 13d, which are extracted from the acting relations in Fig. 5. The degrees of freedom of the motions decrease by the eliminated amount of the yawings of the wheel sets 13a to 13d. Further, measured values to be used for the filter that performs data assimilation such as a Kalman filter increase by the forward-and-backward-direction forces T_1 to T_4 . Accordingly, the accuracy of information of motion to be calculated by performing the operation using the filter that performs data assimilation such as a Kalman filter improves.

[0061] In the meantime, Fig. 7 is a view illustrating acting relations necessary for determining the alignment irregularity amounts y_{R1} to y_{R4} , which are extracted from the acting relations in Fig. 5. The transformation variables e_1 to e_4 and the information of the yawings of the bogies 12a, 12b are already known. Thus, by using the calculation equations of the transformation variables e_1 to e_4 ((26) Equation to (29) Equation in a later-described example), information of the yawings of the wheel sets 13a to 13d is calculated. The transformation variables e_1 to e_4 at this time are directly derived from the measured values of the forward-and-backward-direction forces T_1 to T_4 . Further, the information of the yawings of the bogies 12a, 12b is calculated by using the acting relations in Fig. 6. Thus, the accuracy of the information of the yawings of the wheel sets 13a to 13d calculated from the transformation variables e_1 to e_4 and the information of the yawings of the bogies 12a, 12b improves as compared to the case where it is calculated by using the acting relations in Fig. 4. Further, the information of the yawings of the wheel sets 13a to 13d, the forward-and-backward-direction forces T_1 to T_4 , and the information of the motions of the components directly acting on the yawings of the wheel sets 13a to 13d (the transversal vibrations of the wheel sets 13a to 13d and the transversal vibrations of the bogies 12a, 12b) are already known. Thus, by using the motion equations that describe the yawings of the wheel sets 13a to 13d ((51) Equation to (54) Equation in a later-described example), the alignment irregularity amounts y_{R1} to y_{R4} are calculated. The accuracy of the information of the yawings of the wheel sets 13a to 13d at this time improves as compared to the case where it is calculated by using the acting relations in Fig. 4, as described previously. Further, the forward-and-backward-direction forces T_1 to T_4 are measured values. Further, the information of the motions of the components that directly act on the yawings of the wheel sets 13a to 13d is calculated by using the acting relations in Fig. 6, and thus its accuracy improves. Accordingly, the accuracy of the alignment irregularity amounts y_{R1} to y_{R4} that are calculated as above improves.

[0062] An inspection apparatus 800 to be explained below is an apparatus that embodies one example of the method of improving the accuracy of the alignment irregularity amounts y_{R1} to y_{R4} in the manner found as above.

<Inspection apparatus 800>

[0063] Fig. 8 is a diagram illustrating one example of a functional configuration of an inspection apparatus 800. Fig. 9 is a diagram illustrating one example of a hardware configuration of the inspection apparatus 800. Fig. 10 is a chart illustrating one example of preprocessing in the inspection apparatus 800. Fig. 11 is a chart illustrating one example of main processing in the inspection apparatus 800. In this embodiment, as illustrated in Fig. 1, the case where the inspection apparatus 800 is mounted on the railway vehicle will be explained as an example.

[0064] In Fig. 8, the inspection apparatus 800 includes, as its functions, a state equation storage unit 801, an observation equation storage unit 802, a data acquisition unit 803, a filter operation unit 804, a track state calculation unit 805, and an output unit 806.

[0065] In Fig. 9, the inspection apparatus 800 includes a CPU 901, a main memory 902, an auxiliary memory 903, a communication circuit 904, a signal processing circuit 905, an image processing circuit 906, an I/F circuit 907, a user interface 908, a display 909, and a bus 910.

[0066] The CPU 901 overall controls the entire inspection apparatus 800. The CPU 901 uses the main memory 902 as a work area to execute a program stored in the auxiliary memory 903. The main memory 902 stores data temporarily. The auxiliary memory 903 stores various data, in addition to programs to be executed by the CPU 901. The auxiliary memory 903 stores state equations and observation equations to be described later. The state equation storage unit 801 and the observation equation storage unit 802 are fabricated by using the CPU 901 and the auxiliary memory 903, for example.

[0067] The communication circuit 904 is a circuit intended for performing communication with the outside of the inspection apparatus 800. The communication circuit 904 receives information of the measured value of the forward-and-backward-direction force and information of measured values of accelerations of the vehicle body 11, the bogies 12a, 12b, and the wheel sets 13a to 13d in the right and left direction, for example. The communication circuit 904 may perform radio communication or wire communication with the outside of the inspection apparatus 800. The communication circuit 904 is connected to an antenna provided on the railway vehicle in the case of performing radio communication.

[0068] The signal processing circuit 905 performs various signal processings on signals received in the communication circuit 904 and signals input according to the control by the CPU 901. The data acquisition unit 803 is fabricated by using the CPU 901, the communication circuit 904, and the signal processing circuit 905, for example. Further, the filter operation unit 804 and the track state calculation unit 805 are fabricated by using the CPU 901 and the signal processing circuit 905, for example.

[0069] The image processing circuit 906 performs various image processings on signals input according to the control by the CPU 901. The signal that has been subjected to the image processing is output on the display 909.

[0070] The user interface 908 is a part in which an operator gives an instruction to the inspection apparatus 800. The user interface 908 includes buttons, switches, dials, and so on, for example. Further, the user interface 908 may include a graphical user interface using the display 909.

[0071] The display 909 displays an image based on a signal output from the image processing circuit 906. The I/F circuit 907 exchanges data with a device connected to the I/F circuit 907. In Fig. 9, as the device to be connected to the I/F circuit 907, the user interface 908 and the display 909 are illustrated. However, the device to be connected to the I/F circuit 907 is not limited to these. For example, a portable storage medium may be connected to the I/F circuit 907. Further, at least a part of the user interface 908 and the display 909 may be provided outside the inspection apparatus 800.

[0072] The output unit 806 is fabricated by using the communication circuit 904, the signal processing circuit 905, and at least any one of the image processing circuit 906, the I/F circuit 907, and the display 909, for example.

[0073] Incidentally, the CPU 901, the main memory 902, the auxiliary memory 903, the signal processing circuit 905, the image processing circuit 906, and the I/F circuit 907 are connected to the bus 910. Communication among these components is performed via the bus 910. Further, the hardware of the inspection apparatus 800 is not limited to the one illustrated in Fig. 9 as long as it can perform later-described functions of the inspection apparatus 800.

[State equation storage unit 801, S1001]

[0074] The state equation storage unit 801 stores state equations. In this embodiment, out of the aforementioned motion equations, the motion equations that describe the yawings of the wheel sets 13a to 13d of (5) Equation to (8) Equation are not included in the state equation. The alignment irregularity amounts y_{R1} to y_{R4} are included in (5) Equation to (8) Equation. In the case where (5) Equation to (8) Equation are included in the state equation and filtering by a later-described Kalman filter is performed, a model of the track 16 is required. The alignment irregularity is not described according to the physical law. Accordingly, it is necessary to create the model of the track 16 so that time differentiations of the alignment irregularity amounts y_{R1} to y_{R4} become white noise, for example. Then, uncertainty of the model of the track 16 is liable to affect a result of the filtering by the later-described Kalman filter. Further, by reducing the state equations and reducing the state variables, it is possible to stabilize the operation of the later-described Kalman filter.

[0075] Based on the above findings, in this embodiment, the motion equations that describe the yawings of the wheel sets 13a to 13d of (5) Equation to (8) Equation are not included in the state equation, and the state equation is constituted as follows.

[0076] First, the motion equations that describe the transversal vibrations of the bogies 12a, 12b (motion in the right and left direction) of (9) Equation and (10) Equation, the motion equations that describe the rollings of the bogies 12a, 12b of (13) Equation and (14) Equation, the motion equation that describes the transversal vibration of the vehicle body 11 (motion in the right and left direction) of (15) Equation, the motion equation that describes the yawing of the vehicle body 11 of (16) Equation, the motion equation that describes the rolling of the vehicle body 11 of (17) Equation, the motion equations that describe the yawings of the yaw damper disposed on the bogie 12a and the yaw damper disposed on the bogie 12b of (18) Equation and (19) Equation, and the motion equations that describe the rollings of the air spring (bolster spring) disposed on the bogie 12a and the air spring (bolster spring) disposed on the bogie 12b of (20) Equation and (21) Equation are used as they are to constitute the state equation.

[0077] In the meantime, in the motion equations that describe the transversal vibrations of the wheel sets 13a to 13d (motion in the right and left direction) of (1) Equation to (4) Equation and the motion equations that describe the yawings of the bogies 12a, 12b of (11) Equation and (12) Equation, the pivot amounts (angular displacements) ϕ_{w1} to ϕ_{w4} and the angular velocities $\dot{\phi}_{w1}$ to $\dot{\phi}_{w4}$ of the wheel sets 13a to 13d in the yawing direction are included. As described previously, in this embodiment, the motion equations that describe the yawings of the wheel sets 13a to 13d of (5) Equation to (8) Equation are not included in the state equation. Thus, in this embodiment, results obtained after eliminating these variables from (1) Equation to (4) Equation, (11) Equation, and (12) Equation are used to constitute the state equation in the following manner.

[0078] First, the forward-and-backward-direction forces T_1 to T_4 of the wheel sets 13a to 13d are expressed by (22) Equation to (25) Equation below. In this manner, the forward-and-backward-direction forces T_1 to T_4 are determined according to the differences between the angular displacements ϕ_{w1} to ϕ_{w4} of the wheel sets in the yawing direction and the angular displacements ϕ_{t1} to ϕ_{t2} of the bogies on which these wheel sets are provided in the yawing direction.

[Mathematical equation 11]

[Mathematical equation 11]

$$T_1 = C_{wx} b_1^2 \{ \dot{\psi}_{t1} - \dot{\psi}_{w1} \} + K_{wx} b_1^2 \{ \psi_{t1} - \psi_{w1} \} \quad \cdot \cdot \cdot \quad (22)$$

$$T_2 = C_{wx} b_1^2 \{ \dot{\psi}_{t1} - \dot{\psi}_{w2} \} + K_{wx} b_1^2 \{ \psi_{t1} - \psi_{w2} \} \quad \cdot \cdot \cdot \quad (23)$$

$$T_3 = C_{wx} b_1^2 \{ \dot{\psi}_{t2} - \dot{\psi}_{w3} \} + K_{wx} b_1^2 \{ \psi_{t2} - \psi_{w3} \} \quad \cdot \cdot \cdot \quad (24)$$

$$T_4 = C_{wx} b_1^2 \{ \dot{\psi}_{t2} - \dot{\psi}_{w4} \} + K_{wx} b_1^2 \{ \psi_{t2} - \psi_{w4} \} \quad \cdot \cdot \cdot \quad (25)$$

[0079] The transformation variables e_1 to e_4 are defined like (26) Equation to (29) Equation below. As above, the transformation variables e_1 to e_4 are defined by the differences between the angular displacements ϕ_{t1} to ϕ_{t2} of the bogies in the yawing direction and the angular displacements ϕ_{w1} to ϕ_{w4} of the wheel sets in the yawing direction. The transformation variables e_1 to e_4 are variables for performing mutual transformation between the angular displacements ϕ_{t1} to ϕ_{t2} of the bogies in the yawing direction and the angular displacements ϕ_{w1} to ϕ_{w4} of the wheel sets in the yawing direction.

[Mathematical equation 12]

[Mathematical equation 12]

$$e_1 = \psi_{t1} - \psi_{w1} \quad \cdot \cdot \cdot \quad (26)$$

$$e_2 = \psi_{t1} - \psi_{w2} \quad \cdot \cdot \cdot \quad (27)$$

$$e_3 = \psi_{t2} - \psi_{w3} \quad \cdot \cdot \cdot \quad (28)$$

$$e_4 = \psi_{t2} - \psi_{w4} \quad \cdot \cdot \cdot \quad (29)$$

[0080] When (26) Equation to (29) Equation are deformed, (30) Equation to (33) Equation below are obtained.

[Mathematical equation 13]

[Mathematical equation 13]

$$\psi_{w1} = \psi_{t1} - e_1 \quad \cdot \cdot \cdot \quad (30)$$

$$\psi_{w2} = \psi_{t1} - e_2 \quad \cdot \cdot \cdot \quad (31)$$

$$\psi_{w3} = \psi_{t2} - e_3 \quad \cdot \cdot \cdot \quad (32)$$

$$\psi_{w4} = \psi_{t2} - e_4 \quad \cdot \cdot \cdot \quad (33)$$

[0081] When (30) Equation to (33) Equation are substituted into the motion equations that describe the transversal vibrations of the wheel sets 13a to 13d (motion in the right and left direction) of (1) Equation to (4) Equation, (34) Equation to (37) Equation below are obtained.

[Mathematical equation 14]

[Mathematical equation 14]

$$m_w \ddot{y}_{w1} + \frac{f_2}{v} \dot{y}_{w1} + C_{wy} [\dot{y}_{w1} - \{ \dot{y}_{t1} + a \dot{\psi}_{t1} + h_1 \dot{\phi}_{t1} \}] - f_2 \psi_{t1} + K_{wy} [y_{w1} - \{ y_{t1} + a \psi_{t1} + h_1 \phi_{t1} \}] = -f_2 e_1 \quad \cdot \cdot \cdot \quad (34)$$

$$m_w \ddot{y}_{w2} + \frac{f_2}{V} \dot{y}_{w2} + C_{wy} [\dot{y}_{w2} - \{\dot{y}_{t1} + a \dot{\psi}_{t1} + h_1 \dot{\phi}_{t1}\}] - f_2 \psi_{t1} + K_{wy} [y_{w2} - \{y_{t1} + a \psi_{t1} + h_1 \phi_{t1}\}] = -f_2 e_1$$

. . . (35)

$$m_w \ddot{y}_{w3} + \frac{f_2}{V} \dot{y}_{w3} + C_{wy} [\dot{y}_{w3} - \{\dot{y}_{t2} + a \dot{\psi}_{t2} + h_1 \dot{\phi}_{t2}\}] - f_2 \psi_{t2} + K_{wy} [y_{w3} - \{y_{t2} + a \psi_{t2} + h_1 \phi_{t2}\}] = -f_2 e_3$$

. . . (36)

$$m_w \ddot{y}_{w4} + \frac{f_2}{V} \dot{y}_{w4} + C_{wy} [\dot{y}_{w4} - \{\dot{y}_{t2} + a \dot{\psi}_{t2} + h_1 \dot{\phi}_{t2}\}] - f_2 \psi_{t2} + K_{wy} [y_{w4} - \{y_{t2} + a \psi_{t2} + h_1 \phi_{t2}\}] = -f_2 e_4$$

. . . (37)

[0082] As above, the motion equations that describe the transversal vibrations of the wheel sets 13a to 13d (motion in the right and left direction) of (1) Equation to (4) Equation are expressed by using the transformation variables e_1 to e_4 , thereby making it possible to eliminate the pivot amounts (angular displacements) ϕ_{w1} to ϕ_{w4} of the wheel sets 13a to 13d in the yawing direction that are included in these motion equations.

[0083] When (22) Equation to (25) Equation are substituted into the motion equations that describe the yawings of the bogies 12a, 12b of (11) Equation and (12) Equation, (38) Equation and (39) Equation below are obtained.

[Mathematical equation 15]

[Mathematical equation 15]

$$\begin{aligned} I_{Tz} \ddot{\psi}_{t1} + 2 C_{wy} a^2 \dot{\psi}_{t1} - C_{wy} a \{\dot{y}_{w1} - \dot{y}_{w2}\} \\ + 2 K_{wy} a^2 \psi_{t1} - K_{wy} a \{y_{w1} - y_{w2}\} \\ + 2 k'_0 (b'_0)^2 \{\psi_{t1} - \psi_{y1}\} + 2 k''_2 b_2^2 \{\psi_{t1} - \psi_b\} = -T_1 - T_2 \end{aligned}$$

. . . (38)

$$\begin{aligned} I_{Tz} \ddot{\psi}_{t2} + 2 C_{wy} a^2 \dot{\psi}_{t2} - C_{wy} a \{\dot{y}_{w3} - \dot{y}_{w4}\} \\ + 2 K_{wy} a^2 \psi_{t2} - K_{wy} a \{y_{w3} - y_{w4}\} \\ + 2 k'_0 (b'_0)^2 \{\psi_{t2} - \psi_{y2}\} + 2 k''_2 b_2^2 \{\psi_{t2} - \psi_b\} = -T_3 - T_4 \end{aligned}$$

. . . (39)

[0084] As above, the motion equations that describe the yawings of the bogies 12a, 12b of (11) Equation and (12) Equation are expressed by using the forward-and-backward-direction forces T_1 to T_4 , thereby making it possible to eliminate the angular displacements ϕ_{w1} to ϕ_{w4} and the angular velocities $\dot{\phi}_{w1}$ to $\dot{\phi}_{w4}$ of the wheel sets 13a to 13d in the yawing direction that are included in these motion equations.

[0085] Further, when (26) Equation to (29) Equation are substituted into (22) Equation to (25) Equation, (40) Equation to (43) Equation below are obtained.

[Mathematical equation 16]

[Mathematical equation 16]

$$C_{wx} b_1^2 \dot{e}_1 + K_{wx} b_1^2 e_1 = T_1 \quad \dots (40)$$

$$C_{wx} b_1^2 \dot{e}_2 + K_{wx} b_1^2 e_2 = T_2 \quad \dots (41)$$

$$C_{wx} b_1^2 \dot{e}_3 + K_{wx} b_1^2 e_3 = T_3 \quad \dots (42)$$

$$C_{wx} b_1^2 \dot{e}_4 + K_{wx} b_1^2 e_4 = T_4 \quad \dots (43)$$

[0086] As above, in this embodiment, like (34) Equation to (37) Equation, the motion equations that describe the transversal vibrations of the wheel sets 13a to 13d (motion in the right and left direction) are expressed, and at the same time, like (38) Equation and (39) Equation, the motion equations that describe the yawings of the bogies 12a, 12b are expressed, and by using these, the state equation is constituted. Further, (40) Equation to (43) Equation are ordinary differential equations, and actual values of the transformation variables e_1 to e_4 , which are solutions of the equations, can be derived by using the measured values of the forward-and-backward-direction forces T_1 to T_4 in the wheel sets 13a to 13d.

[0087] The actual values of the transformation variables e_1 to e_4 derived as above are given to (34) Equation to (37) Equation. Further, the measured values of the forward-and-backward-direction forces T_1 to T_4 in the wheel sets 13a to 13d are given to (38) Equation and (39) Equation.

[0088] In this embodiment, variables illustrated in (44) Equation below are set as the state variables, and by using the motion equations of (9) Equation, (10) Equation, (13) Equation to (21) Equation, and (34) Equation to (39) Equation, the state equation is constituted.

[Mathematical equation 17]

[Mathematical equation 17]

$$\text{State variables} = \begin{bmatrix} \dot{y}_{w1} & y_{w1} & \dot{y}_{w2} & y_{w2} & \dot{y}_{w3} & y_{w3} & \dot{y}_{w4} & y_{w4} & \dot{y}_{t1} & y_{t1} & \dot{y}_{t2} & y_{t2} & \dot{\psi}_{t1} & \psi_{t1} & \dot{\psi}_{t2} & \psi_{t2} \\ \dot{\phi}_{t1} & \phi_{t1} & \dot{\phi}_{t2} & \phi_{t2} & \dot{y}_b & y_b & \dot{\psi}_b & \psi_b & \dot{\phi}_b & \phi_b & \psi_{y1} & \psi_{y2} & \phi_{a1} & \phi_{a2} \end{bmatrix} \quad \dots (44)$$

[0089] The state equation storage unit 801 receives the state equation constituted as above, for example, based on the operation of the user interface 908 by an operator and stores it.

[Observation equation storage unit 802, S1002]

[0090] The observation equation storage unit 802 stores observation equations. In this embodiment, the acceleration of the vehicle body 11 in the right and left direction, the accelerations of the bogies 12a, 12b in the right and left direction, and the accelerations of the wheel sets 13a to 13d in the right and left direction are set to observation variables. These observation variables are observation variables of the filtering by the later-described Kalman filter. In this embodiment, the motion equations that describe the transversal vibrations of (34) Equation to (37) Equation, (9) Equation, (10) Equation, and (15) Equation are used to constitute an observation equation. The observation equation storage unit 802 receives the observation equation constituted in this manner, for example, based on the operation of the user interface 908 by an operator and stores it.

[0091] After the state equation and the observation equation are stored in the inspection apparatus 800 as above, the data acquisition unit 803, the filter operation unit 804, the track state calculation unit 805, and the output unit 806 start. That is, after the preprocessing by a flowchart in Fig. 3 is finished, the main processing by a flowchart in Fig. 4 starts.

[Data acquisition unit 803, S1101]

[0092] The data acquisition unit 803 acquires measured data .

[0093] In this embodiment, the data acquisition unit 803 acquires, as the measured data, a measured value of the

acceleration of the vehicle body 11 in the right and left direction, measured values of the accelerations of the bogies 12a, 12b in the right and left direction, and measured values of the accelerations of the wheel sets 13a to 13d in the right and left direction. The respective accelerations are measured by using strain gauges attached to, for example, the vehicle body 11, the bogies 12a, 12b, and the wheel sets 13a to 13d respectively and an arithmetic device that calculates the accelerations by using measured values of these strain gauges. Incidentally, the measurement of the accelerations can be performed by a well-known technique, and thus its detailed explanation is omitted.

[0094] Further, the data acquisition unit 803 acquires, as the measured data, the measured value of the forward-and-backward-direction force. The method of measuring the forward-and-backward-direction force is as described previously.

[0095] The data acquisition unit 803 can acquire the measured data by performing communication with the aforementioned arithmetic device, for example.

[Filter operation unit 804, S1102]

[0096] The filter operation unit 804 sets the observation equation as the observation equation stored by the observation equation storage unit 802, sets the state equation as the state equation stored by the state equation storage unit 801, and determines the state variables illustrated in (44) Equation by using the measured data acquired in the data acquisition unit 803 by the Kalman filter. As described previously, in this embodiment, in the measured data, the measured value of the acceleration of the vehicle body 11 in the right and left direction, the measured values of the accelerations of the bogies 12a, 12b in the right and left direction, the measured values of the accelerations of the wheel sets 13a to 13d in the right and left direction, and the measured values of the forward-and-backward-direction forces T_1 to T_4 in the wheel sets 13a to 13d are contained.

[0097] The Kalman filter is one of the methods of performing data assimilation. That is, the Kalman filter is one example of the method to determine a value of an unobserved variable (state variable) so that the difference between, of an observable variable (observation variable), a measured value and a calculated value becomes small (minimum). The filter operation unit 804 derives a Kalman gain when the difference between, of the observation variable, the measured value and the calculated value becomes small (minimum) and derives the value of the unobserved variable (state variable) at that time. In the Kalman filter, the following observation equation of (45) Equation and the following state equation of (46) Equation are used.

$$Y = HX + V \quad \cdot \quad \cdot \quad \cdot \quad (45)$$

$$\dot{X} = \Phi X + W \quad \cdot \quad \cdot \quad \cdot \quad (46)$$

[0098] In (45) Equation, Y is a vector in which the measured value of the observation variable is stored. H is an observation model. X is a vector in which the state variable is stored. V is observation noise. $\dot{X}$ is a time differentiation of X. Φ is a linear model. W is system noise. Incidentally, the Kalman filter itself can be fabricated by a well-known technique, and thus its detailed explanation is omitted.

[Track state calculation unit 805, S1103]

[0099] When (22) Equation to (25) Equation are substituted into the motion equations that describe the yawings of the wheel sets 13a to 13d of (5) Equation to (8) Equation, (47) Equation to (50) Equation are obtained.

[Mathematical equation 18]

[Mathematical equation 18]

$$I_{wz} \ddot{\psi}_{w1} + \frac{f_1 b^2}{v} \dot{\psi}_{w1} + \frac{f_1 b r}{r} \{y_{w1} - y_{R1}\} + s_a K_{wy} \{y_{w1} - y_{t1}\} + s_a C_{wy} \{\dot{y}_{w1} - \dot{y}_{t1}\} = T_1$$

$$\cdot \quad \cdot \quad \cdot \quad (47)$$

$$I_{wz} \ddot{\psi}_{w2} + \frac{f_1 b^2}{V} \dot{\psi}_{w2} + \frac{f_1 b \gamma}{r} \{y_{w2} - y_{R2}\} + s_a K_{wy} \{y_{w2} - y_{t1}\} + s_a C_{wy} \{\dot{y}_{w2} - \dot{y}_{t1}\} = T_2$$

. . . (48)

$$I_{wz} \ddot{\psi}_{w3} + \frac{f_1 b^2}{V} \dot{\psi}_{w3} + \frac{f_1 b \gamma}{r} \{y_{w3} - y_{R3}\} + s_a K_{wy} \{y_{w3} - y_{t2}\} + s_a C_{wy} \{\dot{y}_{w3} - \dot{y}_{t2}\} = T_3$$

. . . (49)

$$I_{wz} \ddot{\psi}_{w4} + \frac{f_1 b^2}{V} \dot{\psi}_{w4} + \frac{f_1 b \gamma}{r} \{y_{w4} - y_{R4}\} + s_a K_{wy} \{y_{w4} - y_{t2}\} + s_a C_{wy} \{\dot{y}_{w4} - \dot{y}_{t2}\} = T_4$$

. . . (50)

[0100] The track state calculation unit 805 calculates estimated values of the pivot amounts (angular displacements) ϕ_{w1} to ϕ_{w4} of the wheel sets 13a to 13d in the yawing direction by (30) Equation to (33) Equation. Then, the track state calculation unit 805 gives the estimated values of the pivot amounts (angular displacements) ϕ_{w1} to ϕ_{w4} of the wheel sets 13a to 13d in the yawing direction, the state variables illustrated in (48) Equation derived in the filter operation unit 804, and the measured values of the forward-and-backward-direction forces T_1 to T_4 in the wheel sets 13a to 13d to (47) Equation to (50) Equation, to thereby calculate the alignment irregularity amounts y_{R1} to y_{R4} at the positions of the wheel sets 13a to 13d. The state variables to be used here are the displacements y_{t1} to y_{t2} of the bogies 12a, 12b in the right and left direction, the velocities $\dot{y}_{t1}$ to $\dot{y}_{t2}$ of the bogies 12a, 12b in the right and left direction, the displacements y_{w1} to y_{w4} of the wheel sets 13a to 13d in the right and left direction, and the velocities $\dot{y}_{w1}$ to $\dot{y}_{w4}$ of the wheel sets 13a to 13d in the right and left direction.

[0101] Then, the track state calculation unit 805 calculates a final alignment irregularity amount y_R from the alignment irregularity amounts y_{R1} to y_{R4} .

For example, the track state calculation unit 805 calculates, as the alignment irregularity amount y_R , an arithmetic mean value of two values of the alignment irregularity amounts y_{R1} to y_{R4} from which the maximum value and the minimum value are removed. At this time, the track state calculation unit 805 may derive a moving average of each of the alignment irregularity amounts y_{R1} to y_{R4} at the positions of the wheel sets 13a to 13d (namely, pass each of the alignment irregularity amounts y_{R1} to y_{R4} at the positions of the wheel sets 13a to 13d through a lowpass filter) and calculate the final alignment irregularity amount y_R from the alignment irregularity amounts y_{R1} to y_{R4} at the positions of the wheel sets 13a to 13d from which their moving averages have been removed.

[Output unit 806, S1104]

[0102] The output unit 806 outputs information of the alignment irregularity amount y_R calculated by the track state calculation unit 805. At this time, the output unit 806 may output information indicating that the track 16 is abnormal in the case where the alignment irregularity amount y_R is larger than a preset value. As a form of output, it is possible to employ at least any one of displaying the information on a computer display, transmitting the information to an external device, and storing the information in an internal or external storage medium, for example.

<Example>

[0103] Next, there will be explained examples. In this example, there was performed a numerical simulation of the case where such a railway vehicle including the single vehicle body 11 provided with the two bogies 12a, 12b and four sets of the wheel sets 13a to 13d as illustrated in Fig. 1 traveled at 270 km/h. Further, in this example, the axle box suspension is set to the mono-link type axle box suspension. Incidentally, in this example, the forward-and-backward-direction force is referred to as a mono-link force. Then, by using data calculated by this numerical simulation, the alignment irregularity amounts were calculated by the method explained in this embodiment. At this time, a model used for the numerical simulation was set to have 86 degrees of freedom. Accordingly, to the model used for the numerical simulation, motions that are not expected in the model having 21 degrees of freedom, which was used for calculating the alignment irregularity amounts, are added. This example is set as above, and thereby the system noise of the state equation corresponding to the case where an actual railway vehicle has traveled has been obtained. In the meantime,

the observation noise of the observation equation in the case where an actual railway vehicle has traveled relies on measurement accuracy. The observation noise is not contained in observation data in this example. Therefore, this example becomes a case where it is expected that ideal measurement accuracy has been obtained.

[0104] Fig. 12 is a view illustrating (part of) the observation data obtained by the numerical simulation. In Fig. 12, a first wheel set indicates the wheel set 13a. A front bogie indicates the bogie 12a. Transversal vibration acceleration indicates the acceleration in the right and left direction.

[0105] Fig. 13 is a view illustrating one example of an actual measured value 1301 and a calculated value 1302 of the alignment irregularity amount. The actual measured value 1301 is an alignment irregularity amount set when the numerical simulation is performed. As illustrated in Fig. 13, of the alignment irregularity amount, the actual measured value 1301 and the calculated value 1302 agree with each other practically on an acceptable level. Accordingly, it is found out that using the method in this embodiment makes it possible to accurately calculate the alignment irregularity amount.

[0106] On the other hand, without using the mono-link force, the motion equations that describe the yawings of the wheel sets 13a to 13d of (5) Equation to (8) Equation were included in the state equation, the time differentiations of the alignment irregularity amounts y_{R1} to y_{R4} were treated as the white noise, and filtering by the Kalman filter was performed. As a result, the calculation became unstable, failing to obtain estimated results.

<Summary>

[0107] As above, in this embodiment, the inspection apparatus 800 gives the measured values of the accelerations, in the right and left direction, of the vehicle body 11, the bogies 12a, 12b, and the wheel sets 13a to 13d, the measured values of the forward-and-backward-direction forces T_1 to T_4 , and the actual values of the transformation variables e_1 to e_4 to the Kalman filter, to derive the state variables (y_{w1} to y_{w4} , y_{w1} to y_{w4} , y_{t1} to y_{t2} , y_{t1} to y_{t2} , ϕ_{t1} to ϕ_{t2} , ϕ_{t1} to ϕ_{t2} , ϕ_{t1} to ϕ_{t2} , ϕ_{t1} to ϕ_{t2} , y_b to y_b , ϕ_b to ϕ_b , ϕ_b to ϕ_b , ϕ_b to ϕ_b , ϕ_{y1} , ϕ_{y2} , ϕ_{a1} , and ϕ_{a2}). Next, the inspection apparatus 800 uses the pivot amounts (angular displacements) ϕ_{t1} to ϕ_{t2} of the bogies 12a, 12b in the yawing direction that are included in the aforementioned state variables and the actual values of the transformation variables e_1 to e_4 , to then derive the pivot amounts (angular displacements) ϕ_{w1} to ϕ_{w4} of the wheel sets 13a to 13d in the yawing direction. Next, the inspection apparatus 800 substitutes the pivot amounts (angular displacements) ϕ_{w1} to ϕ_{w4} of the wheel sets 13a to 13d in the yawing direction, the aforementioned state variables, and the measured values of the forward-and-backward-direction forces T_1 to T_4 into the motion equations that describe the yawings of the wheel sets 13a to 13d, to calculate the alignment irregularity amounts y_{R1} to y_{R4} at the positions of the wheel sets 13a to 13d. Then, the inspection apparatus 800 calculates the final alignment irregularity amount y_R from the alignment irregularity amounts y_{R1} to y_{R4} . Accordingly, it becomes no longer necessary to constitute, as the motion equations that describe the yawings of the wheel sets 13a to 13d, the state equation by using the motion equations including the alignment irregularity amounts y_{R1} to y_{R4} as variables. Thereby, it becomes no longer necessary to create a model of the track 16, and at the same time, it is possible to reduce the number of state variables. In this embodiment, it is possible to reduce the degrees of freedom of the model to 17 degrees of freedom from 21 degrees of freedom, and at the same time, it is possible to reduce the number of state variables to 30 from 38. Further, the number of measured values to be used in the Kalman filter increases by the forward-and-backward-direction forces T_1 to T_4 .

[0108] On the other hand, as explained in the example, when the motion equations that describe the yawings of the wheel sets 13a to 13d of (5) Equation to (8) Equation are included in the state equation without using the forward-and-backward-direction forces T_1 to T_4 , the calculation sometimes becomes unstable, failing to obtain the estimated results. That is, unless the state variables are selected like the technique described in Patent Literature 2, the calculation sometimes becomes unstable, failing to obtain the estimated results. Further, even if the estimated results are obtained, the accuracy to detect irregularity of the track 16 becomes higher in the method of this embodiment as compared to the method of not selecting the state variables. This is because in this embodiment, not including the motion equations that describe the yawings of the wheel sets 13a to 13d in the state equation and using the measured values of the forward-and-backward-direction forces are achieved.

[0109] Further, the strain gauges can be used as sensors in this embodiment, thus not requiring special sensors. Accordingly, it is possible to accurately detect irregularity of the track 16 (track irregularity) inexpensively. Further, since it not necessary to use special sensors, the strain gauges are attached to a commercial vehicle and the inspection apparatus 800 is mounted on the commercial vehicle, thereby making it possible to detect irregularity of the track 16 in real time during traveling of the commercial vehicle. Accordingly, it is possible to detect irregularity of the track 16 without traveling of an inspection car. However, the strain gauges may be attached to the inspection car and the inspection apparatus 800 may be mounted on the inspection car.

<Modified example>

[0110] In this embodiment, the case of using the Kalman filter has been explained as an example. However, it is not

always necessary to use the Kalman filter as long as a filter that derives the state variables so that the error between, of the observation variable, the measured value and the calculated value becomes minimum or the expected value of this error becomes minimum (that is, a filter that performs data assimilation) is used. For example, a particle filter may be used. Incidentally, as the error between, of the observation variable, the measured value and the calculated value, for example, a square error between, of the observation variable, the measured value and the calculated value is cited.

[0111] Further, in this embodiment, the case of deriving the alignment irregularity amount has been explained as an example. However, it is not always necessary to derive the alignment irregularity amount as long as information that reflects the track irregularity (appearance failure of the track 16) is derived as the information reflecting the state of the track 16. For example, in addition to or in place of the alignment irregularity amount, by performing calculations of (51) Equation to (54) Equation, a lateral force to occur when the railway vehicle travels on a linear track (stress in the right and left direction between the wheel and the rail) may be derived. However, Q_1 , Q_2 , Q_3 , and Q_4 are lateral forces in the wheels 14a, 14b, 14c, and 14d respectively. f_3 represents a spin creep coefficient.

[Mathematical equation 19]

[Mathematical equation 19]

$$Q_1 = \frac{f_2}{v} \dot{y}_{w1} - f_2 \psi_{w1} + f_2 \frac{T_1}{K_{wx} b_1^2} - f_3 \frac{\dot{\psi}_{t1}}{v} + f_3 \frac{\dot{T}_1}{K_{wx} b_1^2 v} \quad \dots (51)$$

$$Q_2 = \frac{f_2}{v} \dot{y}_{w2} - f_2 \psi_{w2} + f_2 \frac{T_2}{K_{wx} b_1^2} - f_3 \frac{\dot{\psi}_{t1}}{v} + f_3 \frac{\dot{T}_2}{K_{wx} b_1^2 v} \quad \dots (52)$$

$$Q_3 = \frac{f_2}{v} \dot{y}_{w3} - f_2 \psi_{w3} + f_2 \frac{T_3}{K_{wx} b_1^2} - f_3 \frac{\dot{\psi}_{t2}}{v} + f_3 \frac{\dot{T}_3}{K_{wx} b_1^2 v} \quad \dots (53)$$

$$Q_4 = \frac{f_2}{v} \dot{y}_{w4} - f_2 \psi_{w4} + f_2 \frac{T_4}{K_{wx} b_1^2} - f_3 \frac{\dot{\psi}_{t2}}{v} + f_3 \frac{\dot{T}_4}{K_{wx} b_1^2 v} \quad \dots (54)$$

[0112] Further, in this embodiment, the case of including the state variables that represent the state of the vehicle body 11 has been explained as an example. However, the vehicle body 11 is a part into which vibrations by acting forces between the wheels 14a to 14d and the track 16 (creep force) propagate finally. Accordingly, it is not necessary to include the state variables representing the state of the vehicle body 11 in the case where the effect by the propagation in the vehicle body 11 is judged to be small, for example. In such a case, out of the motion equations of (1) Equation to (21) Equation, the motion equations that describe the transversal vibration, the yawing, and the rolling of the vehicle body 11 of (15) Equation to (17) Equation and the motion equations that describe the yawing of the yaw damper disposed on the bogie 12a and the yawing of the yaw damper disposed on the bogie 12b of (18) Equation and (19) Equation are no longer required. Further, in the motion equations of (1) Equation to (21) Equation, the value inside {} that includes the state amount relating to the vehicle body (state amount including the subscript of b) and the state amount relating to the vehicle body (state amount including the subscript of b) (for example, the left term $\{\phi_{a2} - \phi_b\}$ on the left side of (21) Equation)) is set to 0 (zero).

[0113] Further, in this embodiment, the case of the bogies 12a, 12b each being a bolsterless bogie has been explained as an example. However, the bogies 12a, 12b are not limited to the bolsterless bogie. Further, in the case where the railway vehicle receives centrifugal force on a curved track or the like, the motion equations are rewritten so as to include this centrifugal force. Besides, according to the components of the railway vehicle, forces that the railway vehicle receives, the directions of the motions of the railway vehicle, or the like, the motion equations are rewritten appropriately. That is, the motion equations are not limited to the ones explained in this embodiment as an example.

(Second embodiment)

[0114] Next, there will be explained a second embodiment.

[0115] In the first embodiment, the case where the inspection apparatus 800 mounted on the railway vehicle calculates

the alignment irregularity amount y_R has been explained as an example. In contrast to this, in this embodiment, a data processing device in which some functions of the inspection apparatus 800 are mounted is disposed in an operation center. The data processing device receives measured data transmitted from the railway vehicle and calculates the alignment irregularity amount y_R by using the received measured data. In this manner, in this embodiment, the functions that the inspection apparatus 800 in the first embodiment has are shared and executed by the railway vehicle and the operation center. Constitutions and processing due to this are mainly different between this embodiment and the first embodiment. Accordingly, in the explanation of this embodiment, the same reference numerals and symbols as those added to Fig. 1 to Fig. 13 are added to the same parts as those in the first embodiment, or the like, and their detailed explanations are omitted.

[0116] Fig. 14 is a view illustrating one example of a configuration of an inspection system. In Fig. 14, the inspection system includes data collecting devices 1410a, 1410b, and a data processing device 1420. In Fig. 14, one example of functional configurations of the data collecting devices 1410a, 1410b and the data processing device 1420 is also illustrated. Incidentally, each hardware of the data collecting devices 1410a, 1410b and the data processing device 1420 can be fabricated by the one illustrated in Fig. 9, for example. Accordingly, detailed explanations of the hardware configurations of the data collecting devices 1410a, 1410b and the data processing device 1420 are omitted.

[0117] The data collecting devices 1410a, 1410b are mounted on each railway vehicle one by one. The data processing device 1420 is disposed at the operation center. The operation center centrally manages operations of a plurality of railway vehicles, for example.

<Data collecting devices 1410a, 1410b>

[0118] The data collecting devices 1410a, 1410b can be fabricated by the same components. The data collecting devices 1410a, 1410b include data acquisition units 1411a, 1411b and data transmission units 1412a, 1412b.

[Data acquisition units 1411a, 1411b]

[0119] The data acquisition units 1411a, 1411b have the same function as that of the data acquisition unit 803. That is, the data acquisition units 1411a, 1411b acquire measured data. In this embodiment as well, similarly to the first embodiment, the data acquisition units 1411a, 1411b acquire, as the measured data, a measured value of acceleration of the vehicle body 11 in the right and left direction, measured values of accelerations of the bogies 12a, 12b in the right and left direction, measured values of accelerations of the wheel sets 13a to 13d in the right and left direction, and a measured value of a forward-and-backward-direction force. Strain gauges and an arithmetic device for obtaining these measured values are the same as those explained in the first embodiment.

[Data transmission units 1412a, 1412b]

[0120] The data transmission units 1412a, 1412b transmit the measured data acquired in the data acquisition units 1411a, 1411b to the data processing device 1420. In this embodiment, the data transmission units 1412a, 1412b transmit the measured data acquired in the data acquisition units 1411a, 1411b to the data processing device 1420 by radio. At this time, the data transmission units 1412a, 1412b add identification numbers of the railway vehicles in which the data collecting devices 1410a, 1410b are mounted to the measured data acquired in the data acquisition units 1411a, 1411b. In this manner, the data transmission units 1412a, 1412b transmit the measured data with the identification numbers of the railway vehicles added thereto.

<Data processing device 1420>

[Data reception unit 1421]

[0121] A data reception unit 1421 receives the measured data transmitted by the data transmission units 1412a, 1412b. To the measured data, the identification numbers of the railway vehicles, which are transmission sources of the measured data, have been added.

[Data storage unit 1422]

[0122] A data storage unit 1422 stores the measured data received in the data reception unit 1421. The data storage unit 1422 stores the measured data every identification number of the railway vehicle. The data storage unit 1422 specifies the position of the railway vehicle at the time of receipt of the measured data based on the current operation situation of the railway vehicle and the time of receipt of the measured data, and stores information of the specified

position and the measured data in association with each other. Incidentally, the data collecting devices 1410a, 1410b may collect the information of the current position of the railway vehicle and contain the collected information in the measured data.

5 [Data reading unit 1423]

[0123] A data reading unit 1423 reads the measured data stored in the data storage unit 1422. The data reading unit 1423 can read, out of the measured data stored in the data storage unit 1422, the measured data designated by an operator. Further, the data reading unit 1423 can also read the measured data matching with a preset condition at a
10 preset, timing. In this embodiment, the measured data read by the data reading unit 1423 are determined based on at least any one of the identification number and the position of the railway vehicle, for example.

[0124] A state equation storage unit 801, an observation equation storage unit 802, a filter operation unit 804, a track state calculation unit 805, and an output unit 806 are the same as those explained in the first embodiment. Accordingly, their detailed explanations are omitted here. Incidentally, the filter operation unit 804 uses the measured data read by
15 the data reading unit 1423 in place of using the measured data acquired in the data acquisition unit 803, and determines the state variables illustrated in (44) Equation.

<Summary>

[0125] As above, in this embodiment, the data collecting devices 1410a, 1410b mounted in the railway vehicles collect the measured data to transmit them to the data processing device 1420. The data processing device 1420 disposed at the operation center stores the measured data received from the data collecting devices 1410a, 1410b and uses the stored measured data to calculate the alignment irregularity amount y_R . Accordingly, in addition to the effects explained in the first embodiment, for example, the following effects are exhibited. That is, the data processing device 1420 can
20 calculate the alignment irregularity amount y_R at an arbitrary timing by reading the measured data at an arbitrary timing. Further, the data processing device 1420 can output time-series variation of the alignment irregularity amount y_R at the same position. Further, the data processing device 1420 can output each alignment irregularity amount y_R of a plurality of lines every line.

30 <Modified example>

[0126] In this embodiment, the case where the data collecting devices 1410a, 1410b directly transmit the measured data to the data processing device 1420 has been explained as an example. However, it is not always necessary to constitute this embodiment as above. An inspection system may be built by utilizing cloud computing, for example. Besides, it is possible to employ the various modified examples explained in the first embodiment also for this embodiment.
35

[0127] Further, in the first embodiment and the second embodiment, the case where the state equation storage unit 801, the observation equation storage unit 802, the filter operation unit 804, the track state calculation unit 805, and the output unit 806 are included in one apparatus has been explained as an example. However, it is not always necessary to constitute these embodiments as above. Functions of the state equation storage unit 801, the observation equation storage unit 802, the filter operation unit 804, the track state calculation unit 805, and the output unit 806 may be fabricated by a plurality of apparatuses. In this case, the inspection system is constituted by using the plural apparatuses.
40

(Another embodiment)

[0128] The embodiments of the present invention explained above can be fabricated by causing a computer to execute a program. Further, a computer-readable recording medium in which the aforementioned program is recorded and a computer program product such as the aforementioned program can also be applied as the embodiment of the present invention. As the recording medium, it is possible to use a flexible disk, a hard disk, an optical disk, a magneto-optic disk, a CD-ROM, a magnetic tape, a nonvolatile memory card, a ROM, or the like, for example.
45

[0129] Further, the embodiments of the present invention explained above merely illustrate concrete examples of implementing the present invention, and the technical scope of the present invention is not to be construed in a restrictive manner by these embodiments. That is, the present invention may be implemented in various forms without departing from the technical spirit or main features thereof.
50

55 INDUSTRIAL APPLICABILITY

[0130] The present invention can be utilized for inspecting tracks of railway vehicles, for example.

Claims

1. An inspection system, comprising:

5 a data acquisition means that acquires measured data being data of measured values to be measured by causing a railway vehicle including a vehicle body, a bogie, and a wheel set to travel on a track;
 a filter operation means that performs an operation using a filter performing data assimilation by using the measured data, a state equation, and an observation equation, and thereby determines state variables being variables to be determined in the state equation; and
 10 a track state calculation means that derives information reflecting a state of the track, wherein the measured data contain measured values of accelerations of the bogie and the wheel set in a right and left direction and a measured value of a forward-and-backward-direction force,
 the right and left direction is a direction vertical to both a forward and backward direction being a direction along a traveling direction of the railway vehicle and an up and down direction being a direction vertical to the track,
 15 the forward-and-backward-direction force is a force in the forward and backward direction to occur in a member disposed between the wheel set and the bogie on which the wheel set is provided, and is a force to be determined according to a difference between an angular displacement of the wheel set in a yawing direction and an angular displacement of the bogie on which the wheel set is provided in the yawing direction,
 the member is a member for supporting an axle box,
 20 the yawing direction is a pivoting direction with the up and down direction set as a pivot axis,
 the state equation is an equation described by using the state variables, the forward-and-backward-direction force, and a transformation variable,
 the state variables include a displacement and a velocity of the bogie in the right and left direction, an angular displacement and an angular velocity of the bogie in the yawing direction, an angular displacement and an
 25 angular velocity of the bogie in a rolling direction, a displacement and a velocity of the wheel set in the right and left direction, and an angular displacement of an air spring attached to the railway vehicle in the rolling direction, and do not include an angular displacement or an angular velocity of the wheel set in the yawing direction,
 the rolling direction is a pivoting direction with the forward and backward direction set as a pivot axis,
 the transformation variable is a variable that performs mutual transformation between the angular displacement of the wheel set in the yawing direction and the angular displacement of the bogie in the yawing direction,
 30 the observation equation is an equation described by using an observation variable and the transformation variable,
 the observation variable includes the accelerations of the bogie and the wheel set in the right and left direction,
 the filter operation means uses the state equation into which a measured value of the observation variable, the measured value of the forward-and-backward-direction force, and an actual value of the transformation variable
 35 are substituted and the observation equation into which the actual value of the transformation variable is substituted, and determines the state variables when an error between, of the observation variable, the measured value and a calculated value or an expected value of the error becomes minimum,
 the track state calculation means uses the angular displacement of the bogie in the yawing direction, which is one of the state variables determined by the filter operation means, and the actual value of the transformation
 40 variable to derive an estimated value of the angular displacement of the wheel set in the yawing direction, and uses the derived estimated value of the angular displacement of the wheel set in the yawing direction to derive the information reflecting the state of the track, and
 the actual value of the transformation variable is derived by using the measured value of the forward-and-backward-direction force.
 45

2. The inspection system according to claim 1, wherein

the state equation is constituted by using a motion equation that describes motion of the wheel set in the right and left direction, a motion equation that describes motion of the bogie in the right and left direction, a motion equation
 50 that describes motion of the bogie in the yawing direction, a motion equation that describes motion of the bogie in the rolling direction, and a motion equation that describes motion of the air spring in the rolling direction,
 the motion equation that describes the motion of the wheel set in the right and left direction is a motion equation described by using the transformation variable in place of using the angular displacement of the wheel set in the yawing direction,
 55 the motion equation that describes the motion of the bogie in the yawing direction is a motion equation described by using the forward-and-backward-direction force in place of using the angular displacement and the angular velocity of the wheel set in the yawing direction, and
 the transformation variable is represented by a difference between the angular displacement of the bogie in the

yawing direction and the angular displacement of the wheel set in the yawing direction.

3. The inspection system according to claim 1 or 2, wherein
the data acquisition means further acquires a measured value of acceleration of the vehicle body in the right and left direction,
the observation variable further includes the acceleration of the vehicle body in the right and left direction,
the state variables further include a displacement and a velocity of the vehicle body in the right and left direction,
an angular displacement and an angular velocity of the vehicle body in the yawing direction, an angular displacement and an angular velocity of the vehicle body in the rolling direction, and an angular displacement of a yaw damper attached to the railway vehicle in the yawing direction, and
the filter operation means determines the state variables when differences between, of the accelerations of the vehicle body, the bogie, and the wheel set in the right and left direction, the measured values and calculated values become minimum.
4. The inspection system according to claim 3, wherein
the state equation is constituted by further using a motion equation that describes motion of the vehicle body in the right and left direction, a motion equation that describes motion of the vehicle body in the yawing direction, a motion equation that describes motion of the vehicle body in the rolling direction, and a motion equation that describes motion of the yaw damper in the yawing direction.
5. The inspection system according to any one of claims 1 to 4, wherein
the observation equation is constituted by further using the motion equation that describes the motion of the wheel set in the right and left direction and the motion equation that describes the motion of the bogie in the right and left direction, and
the motion equation that describes the motion of the wheel set in the right and left direction is a motion equation described by using the transformation variable in place of using the angular displacement of the wheel set in the yawing direction.
6. The inspection system according to claim 5, wherein
the observation equation is constituted by further using the motion equation that describes the motion of the vehicle body in the right and left direction.
7. The inspection system according to any one of claims 1 to 6, wherein
the track state calculation means derives an alignment irregularity amount of the track as the information reflecting the state of the track based on the displacement and the velocity of the bogie in the right and left direction being the state variables determined by the filter operation means, the displacement and the velocity of the wheel set in the right and left direction being the state variables determined by the filter operation means, the estimated value of the angular displacement of the wheel set in the yawing direction, the measured value of the forward-and-backward-direction force, and the motion equation that describes the motion of the wheel set in the yawing direction, and
the motion equation that describes the motion of the wheel set in the yawing direction includes the forward-and-backward-direction force and the alignment irregularity amount of the track as variables.
8. The inspection system according to any one of claims 1 to 7, wherein
the track state calculation means derives a lateral force, which is a stress in the right and left direction between a wheel provided on the wheel set and the track, as the information reflecting the state of the track based on the angular displacement of the wheel set in the yawing direction and the velocity of the wheel set in the right and left direction included in the state variables.
9. The inspection system according to any one of claims 1 to 8, wherein
the forward-and-backward-direction force is, out of components in the forward and backward direction of forces to occur in the two members attached to both sides of the single wheel set in the right and left direction, the component opposite in phase to each other.
10. The inspection system according to claim 9, wherein
the member is a link supporting the axle box, or a rubber bush attached to a link supporting the axle box.
11. The inspection system according to claim 9, wherein
the member is an axle beam supporting the axle box, or a rubber bush attached to an axle beam supporting the

axle box.

12. The inspection system according to claim 9, wherein
the member is a leaf spring supporting the axle box, or a rubber bush attached to a leaf spring supporting the axle box.

13. The inspection system according to any one of claims 1 to 12, wherein
the filter is a Kalman filter.

14. The inspection system according to any one of claims 1 to 13, further comprising:

a transmission means that transmits the measured data acquired by the data acquisition means; and
a reception means that receives the measured data transmitted by the transmission means, wherein
the filter operation means uses the measured data received by the reception means, the state equation, and
the observation equation to determine the state variables.

15. An inspection method, comprising:

a data acquisition step of acquiring measured data being data of measured values to be measured by causing
a railway vehicle including a vehicle body, a bogie, and a wheel set to travel on a track;

a filter operation step of performing an operation using a filter performing data assimilation by using the measured
data, a state equation, and an observation equation, and thereby determining state variables being variables
to be determined in the state equation; and

a track state calculation step of deriving information reflecting a state of the track, wherein
the measured data contain measured values of accelerations of the bogie and the wheel set in a right and left
direction and a measured value of a forward-and-backward-direction force,

the right and left direction is a direction vertical to both a forward and backward direction being a direction along
a traveling direction of the railway vehicle and an up and down direction being a direction vertical to the track,
the forward-and-backward-direction force is a force in the forward and backward direction to occur in a member
disposed between the wheel set and the bogie on which the wheel set is provided, and is a force to be determined
according to a difference between an angular displacement of the wheel set in a yawing direction and an angular
displacement of the bogie on which the wheel set is provided in the yawing direction,

the member is a member for supporting an axle box,

the yawing direction is a pivoting direction with the up and down direction set as a pivot axis,

the state equation is an equation described by using the state variables, the forward-and-backward-direction
force, and a transformation variable,

the state variables include a displacement and a velocity of the bogie in the right and left direction, an angular
displacement and an angular velocity of the bogie in the yawing direction, an angular displacement and an
angular velocity of the bogie in a rolling direction, a displacement and a velocity of the wheel set in the right and
left direction, and an angular displacement of an air spring attached to the railway vehicle in the rolling direction,
and do not include an angular displacement or an angular velocity of the wheel set in the yawing direction,

the rolling direction is a pivoting direction with the forward and backward direction set as a pivot axis,

the transformation variable is a variable that performs mutual transformation between the angular displacement
of the wheel set in the yawing direction and the angular displacement of the bogie in the yawing direction,

the observation equation is an equation described by using an observation variable and the transformation
variable,

the observation variable includes the accelerations of the bogie and the wheel set in the right and left direction,
the filter operation step uses the state equation into which a measured value of the observation variable, the
measured value of the forward-and-backward-direction force, and an actual value of the transformation variable
are substituted and the observation equation into which the actual value of the transformation variable is sub-
stituted, and determines the state variables when an error between, of the observation variable, the measured
value and a calculated value or an expected value of the error becomes minimum,

the track state calculation step uses the angular displacement of the bogie in the yawing direction, which is one
of the state variables determined by the filter operation step, and the actual value of the transformation variable
to derive an estimated value of the angular displacement of the wheel set in the yawing direction, and uses the
derived estimated value of the angular displacement of the wheel set in the yawing direction to derive the
information reflecting the state of the track, and

the actual value of the transformation variable is derived by using the measured value of the forward-and-
backward-direction force.

16. A program causing a computer to execute steps comprising:

a data acquisition step of acquiring measured data being data of measured values to be measured by causing a railway vehicle including a vehicle body, a bogie, and a wheel set to travel on a track;

a filter operation step of performing an operation using a filter performing data assimilation by using the measured data, a state equation, and an observation equation, and thereby determining state variables being variables to be determined in the state equation; and

a track state calculation step of deriving information reflecting a state of the track, wherein the measured data contain measured values of accelerations of the bogie and the wheel set in a right and left direction and a measured value of a forward-and-backward-direction force, the right and left direction is a direction vertical to both a forward and backward direction being a direction along a traveling direction of the railway vehicle and an up and down direction being a direction vertical to the track, the forward-and-backward-direction force is a force in the forward and backward direction to occur in a member disposed between the wheel set and the bogie on which the wheel set is provided, and is a force to be determined according to a difference between an angular displacement of the wheel set in a yawing direction and an angular displacement of the bogie on which the wheel set is provided in the yawing direction, the member is a member for supporting an axle box, the yawing direction is a pivoting direction with the up and down direction set as a pivot axis, the state equation is an equation described by using the state variables, the forward-and-backward-direction force, and a transformation variable, the state variables include a displacement and a velocity of the bogie in the right and left direction, an angular displacement and an angular velocity of the bogie in the yawing direction, an angular displacement and an angular velocity of the bogie in a rolling direction, a displacement and a velocity of the wheel set in the right and left direction, and an angular displacement of an air spring attached to the railway vehicle in the rolling direction, and do not include an angular displacement or an angular velocity of the wheel set in the yawing direction, the rolling direction is a pivoting direction with the forward and backward direction set as a pivot axis, the transformation variable is a variable that performs mutual transformation between the angular displacement of the wheel set in the yawing direction and the angular displacement of the bogie in the yawing direction, the observation equation is an equation described by using an observation variable and the transformation variable, the observation variable includes the accelerations of the bogie and the wheel set in the right and left direction, the filter operation step uses the state equation into which a measured value of the observation variable, the measured value of the forward-and-backward-direction force, and an actual value of the transformation variable are substituted and the observation equation into which the actual value of the transformation variable is substituted, and determines the state variables when an error between, of the observation variable, the measured value and a calculated value or an expected value of the error becomes minimum, the track state calculation step uses the angular displacement of the bogie in the yawing direction, which is one of the state variables determined by the filter operation step, and the actual value of the transformation variable to derive an estimated value of the angular displacement of the wheel set in the yawing direction, and uses the derived estimated value of the angular displacement of the wheel set in the yawing direction to derive the information reflecting the state of the track, and the actual value of the transformation variable is derived by using the measured value of the forward-and-backward-direction force.

FIG. 1

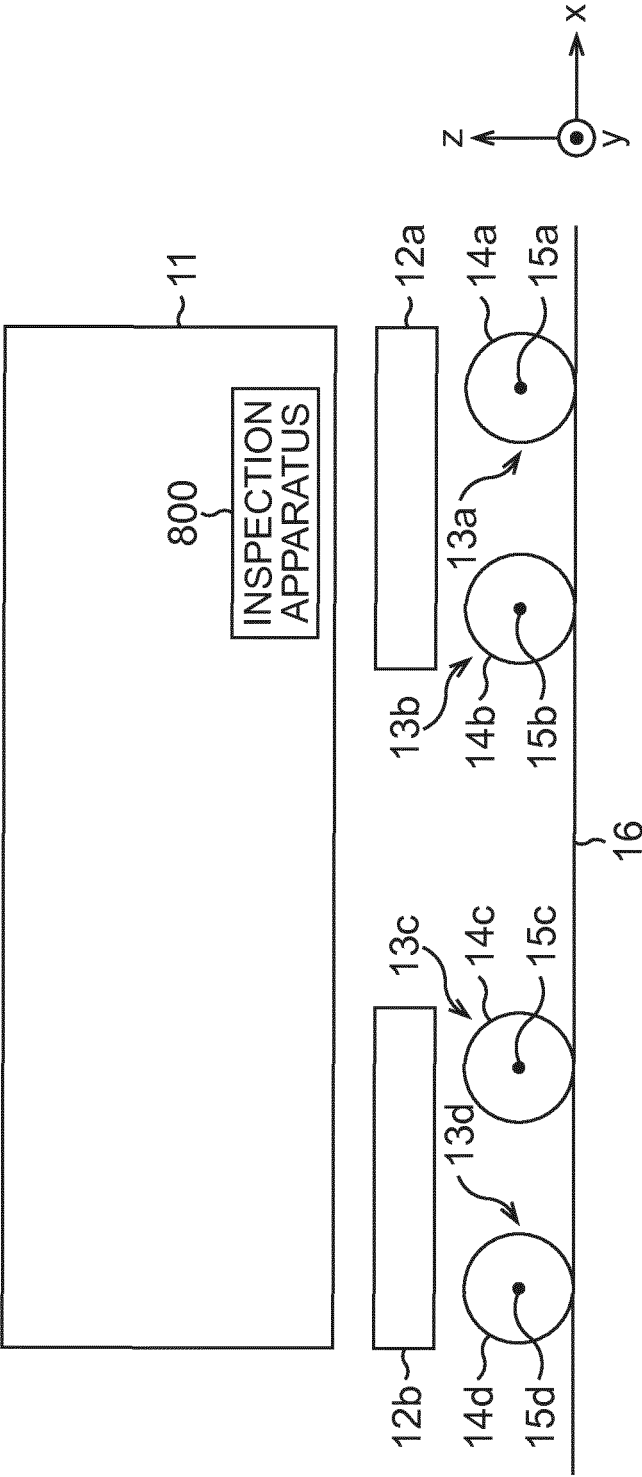


FIG. 2

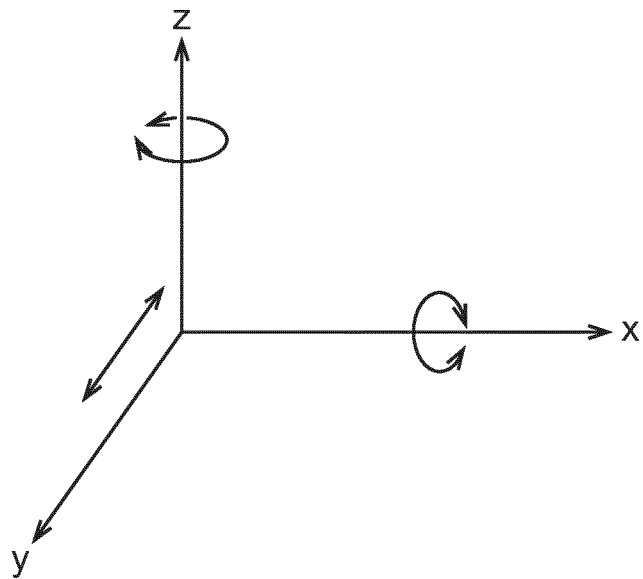


FIG. 3

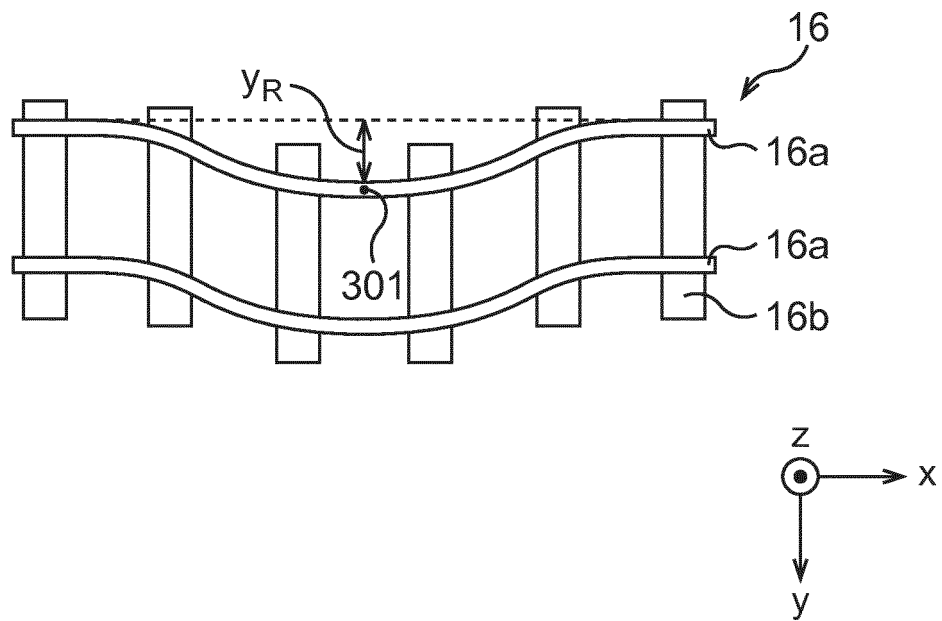


FIG. 4

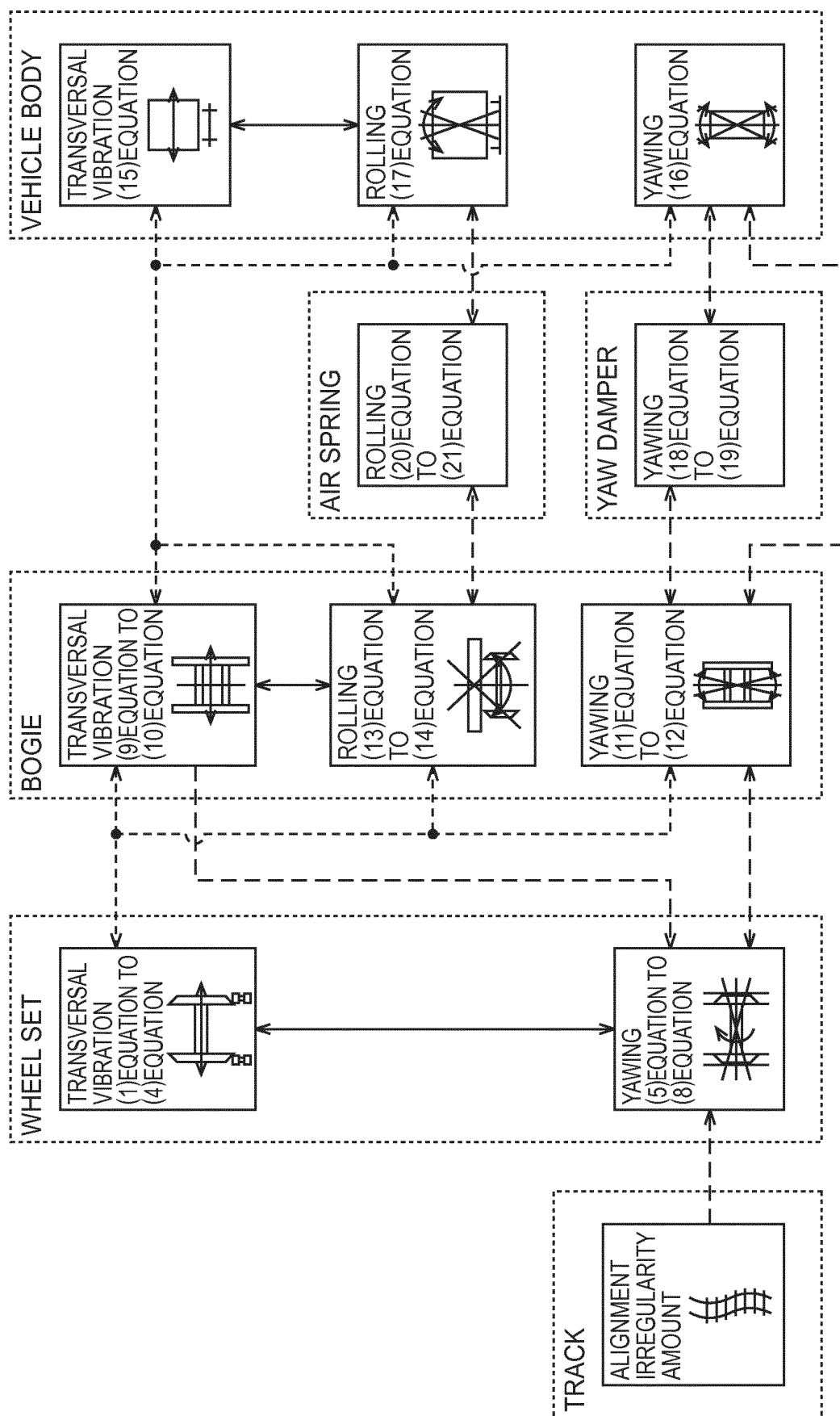


FIG. 5

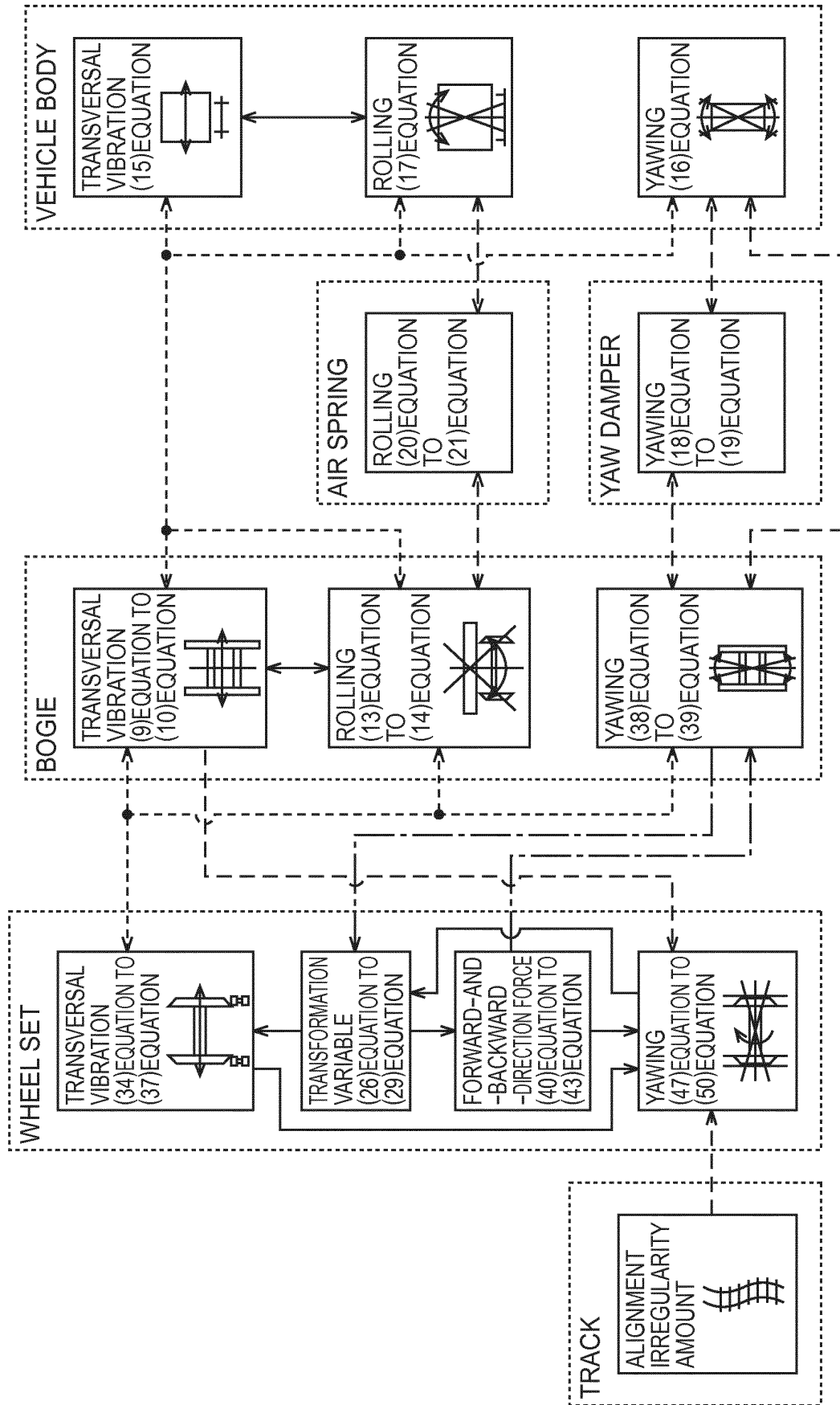


FIG. 6

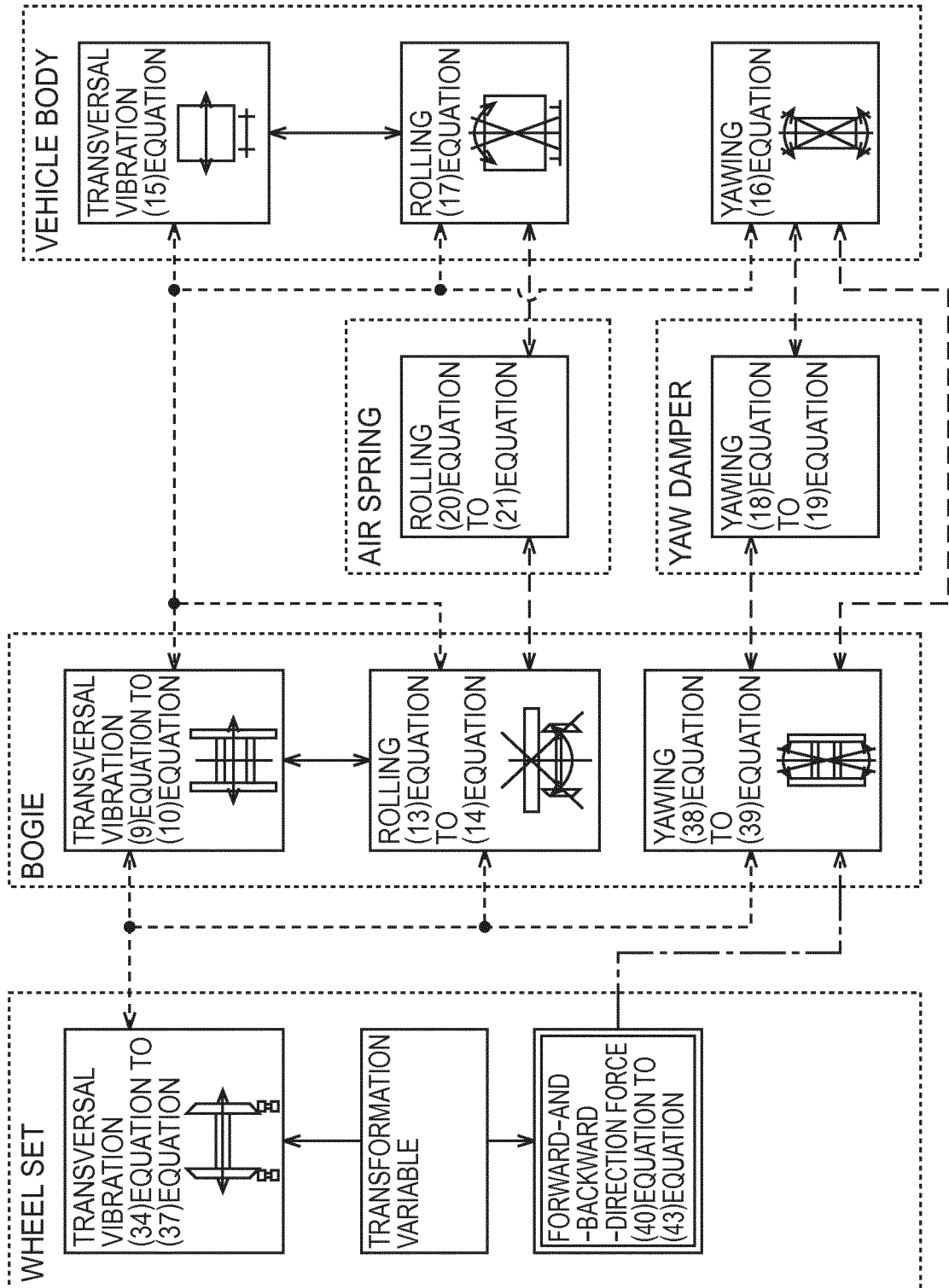


FIG. 7

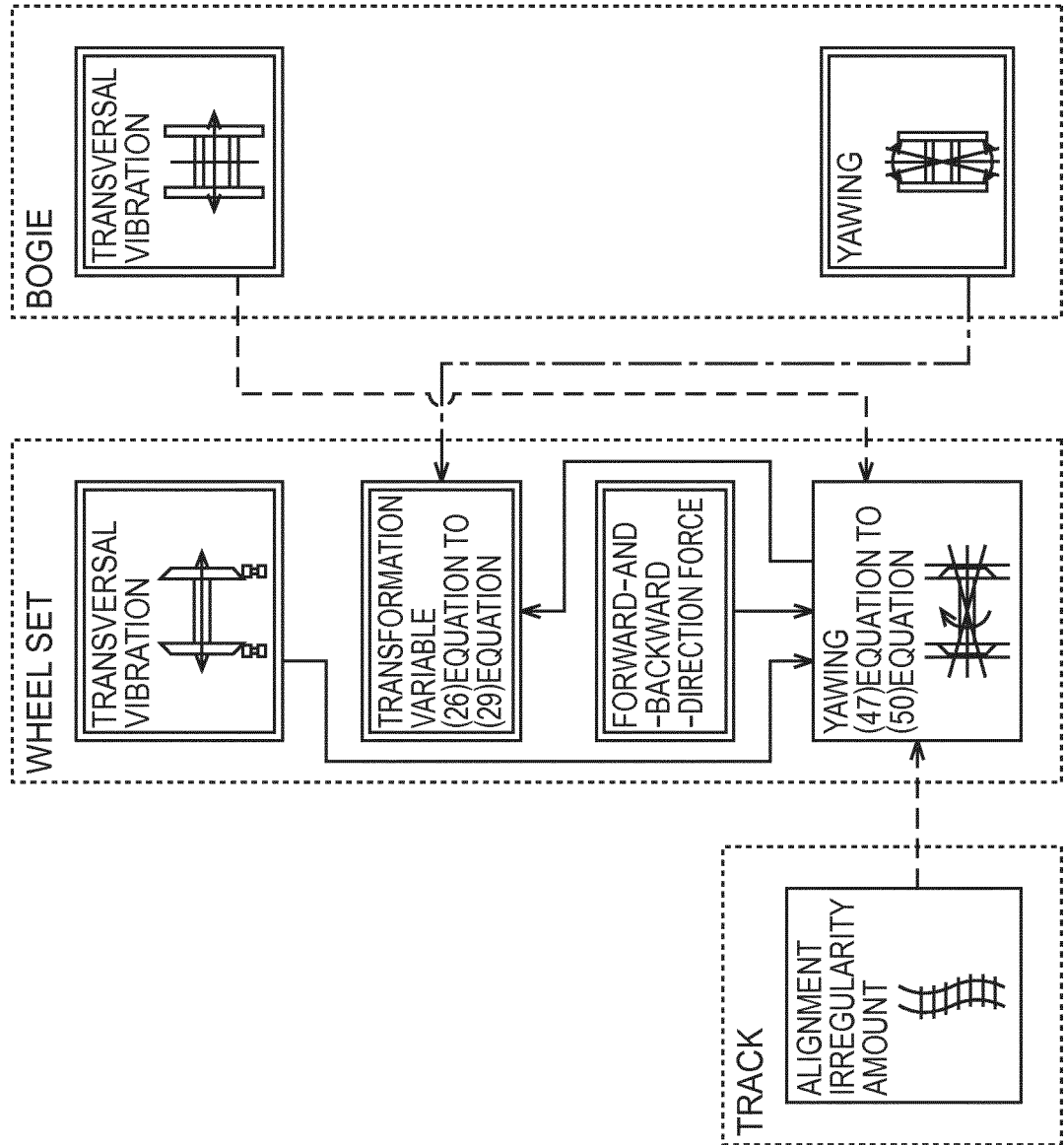


FIG. 8

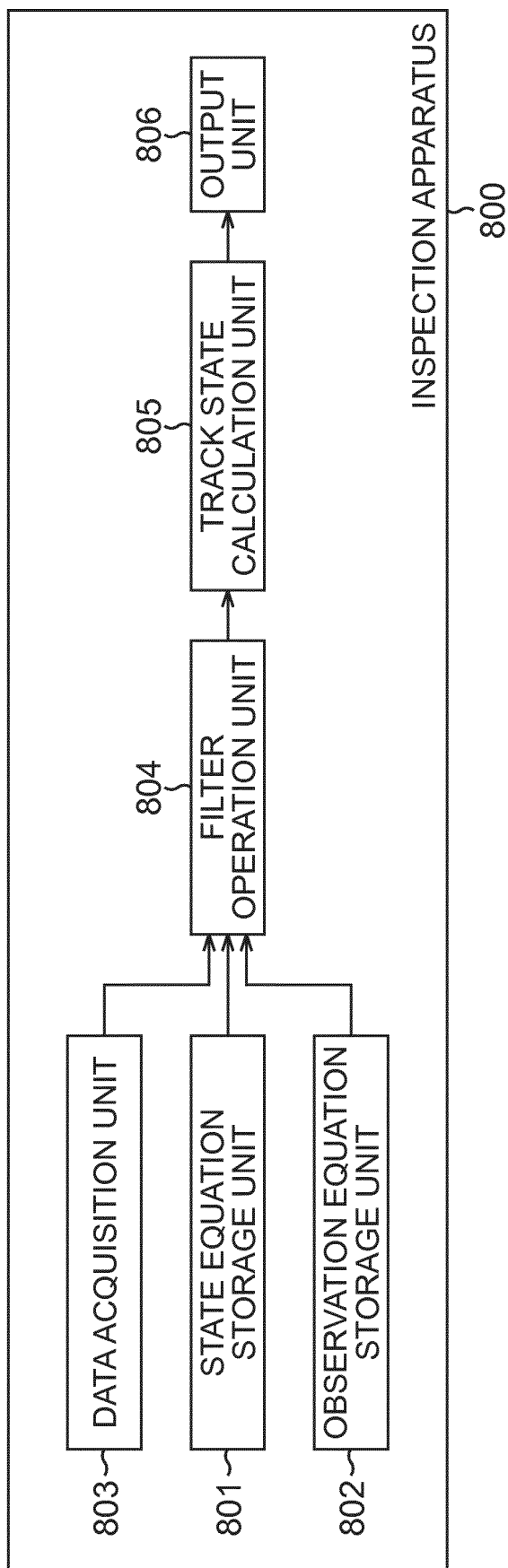


FIG. 9

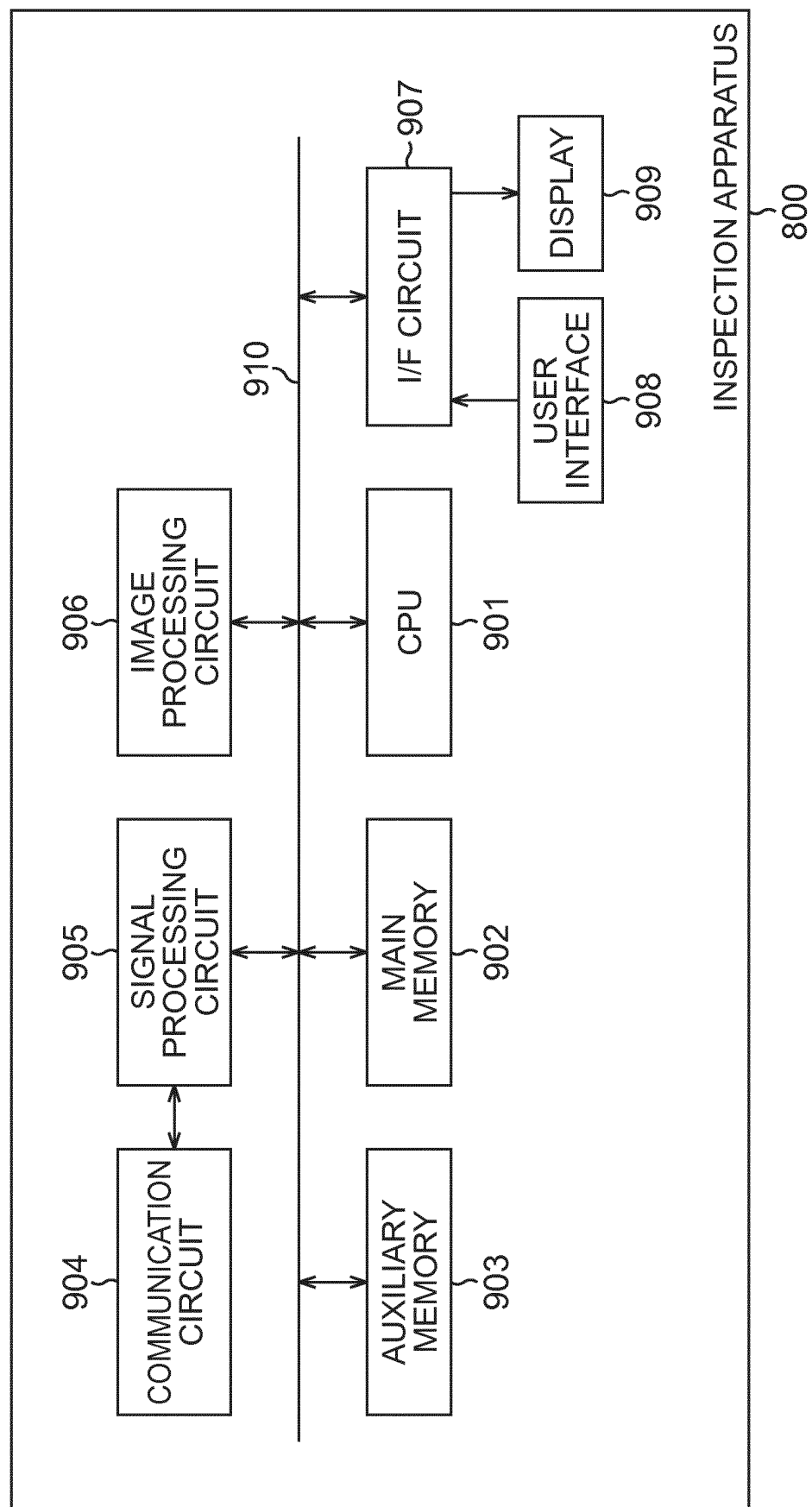


FIG. 10

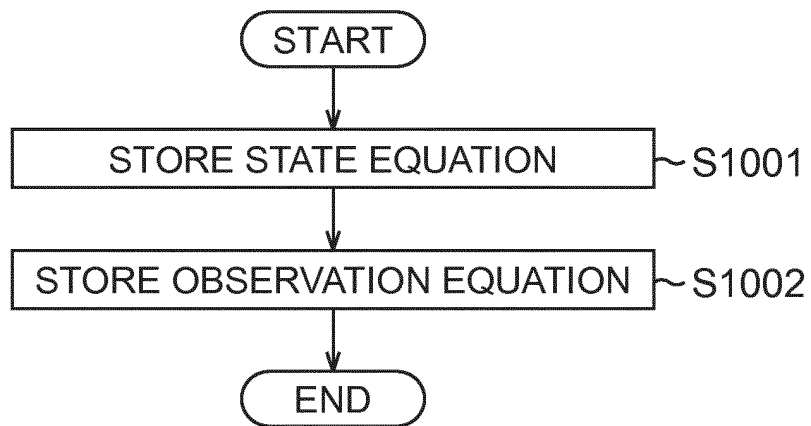


FIG. 11

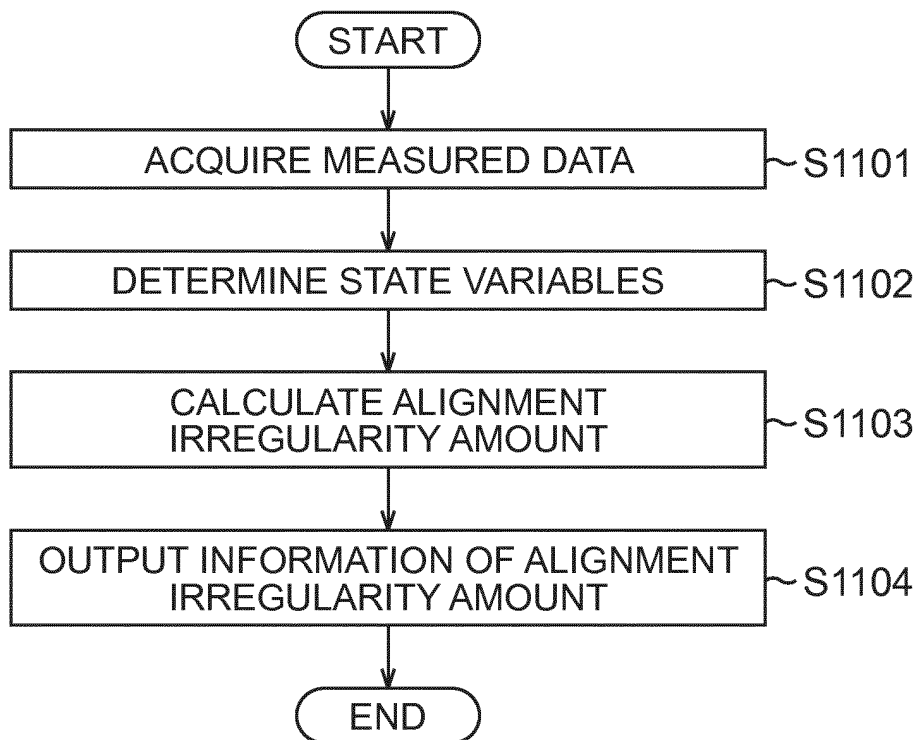


FIG. 12

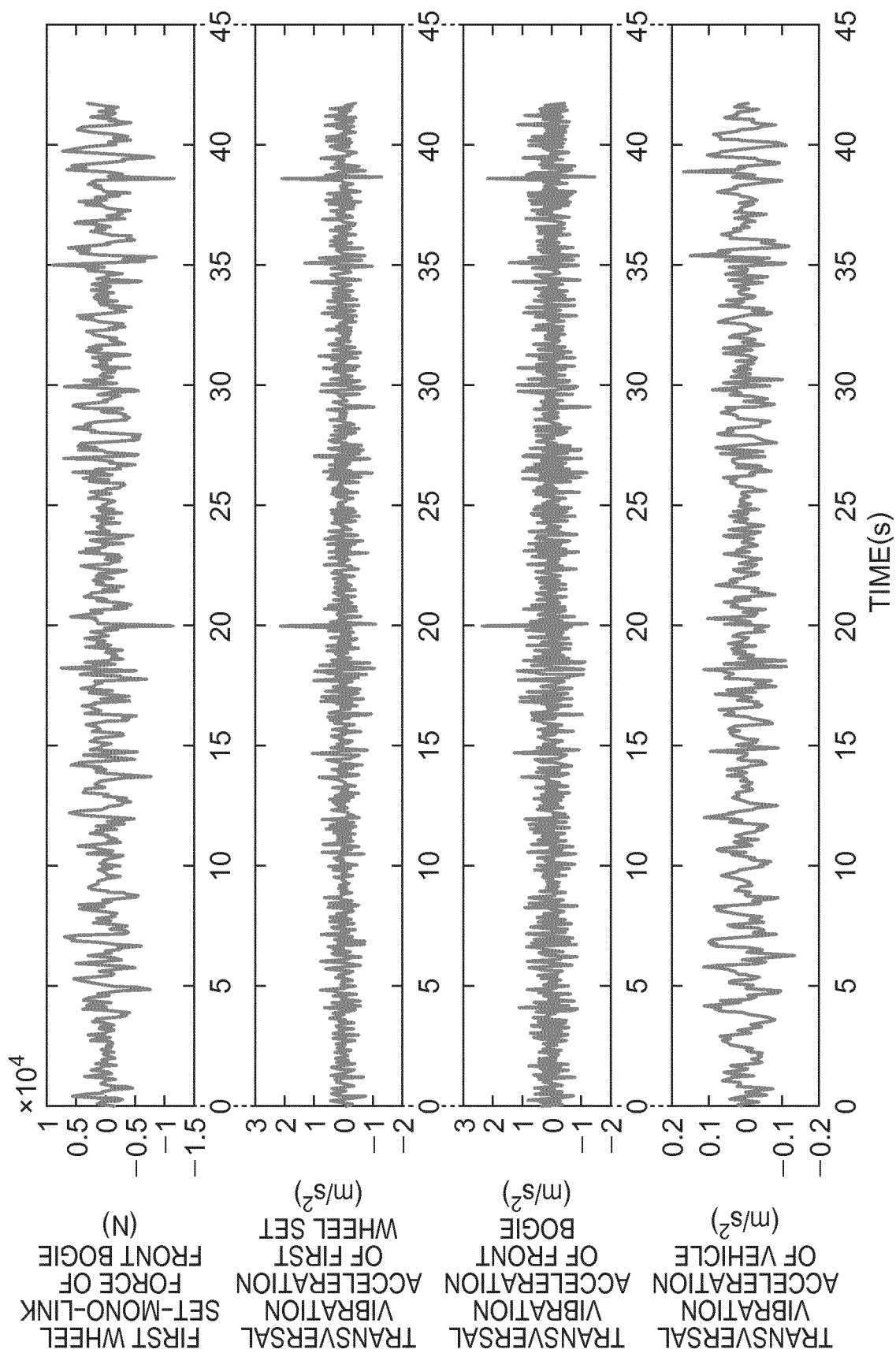


FIG. 13

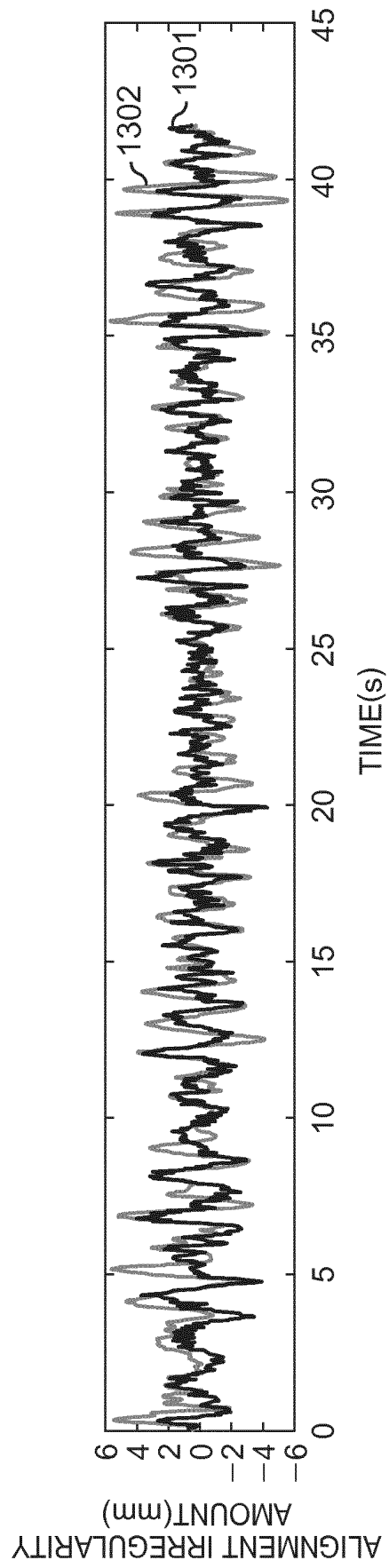
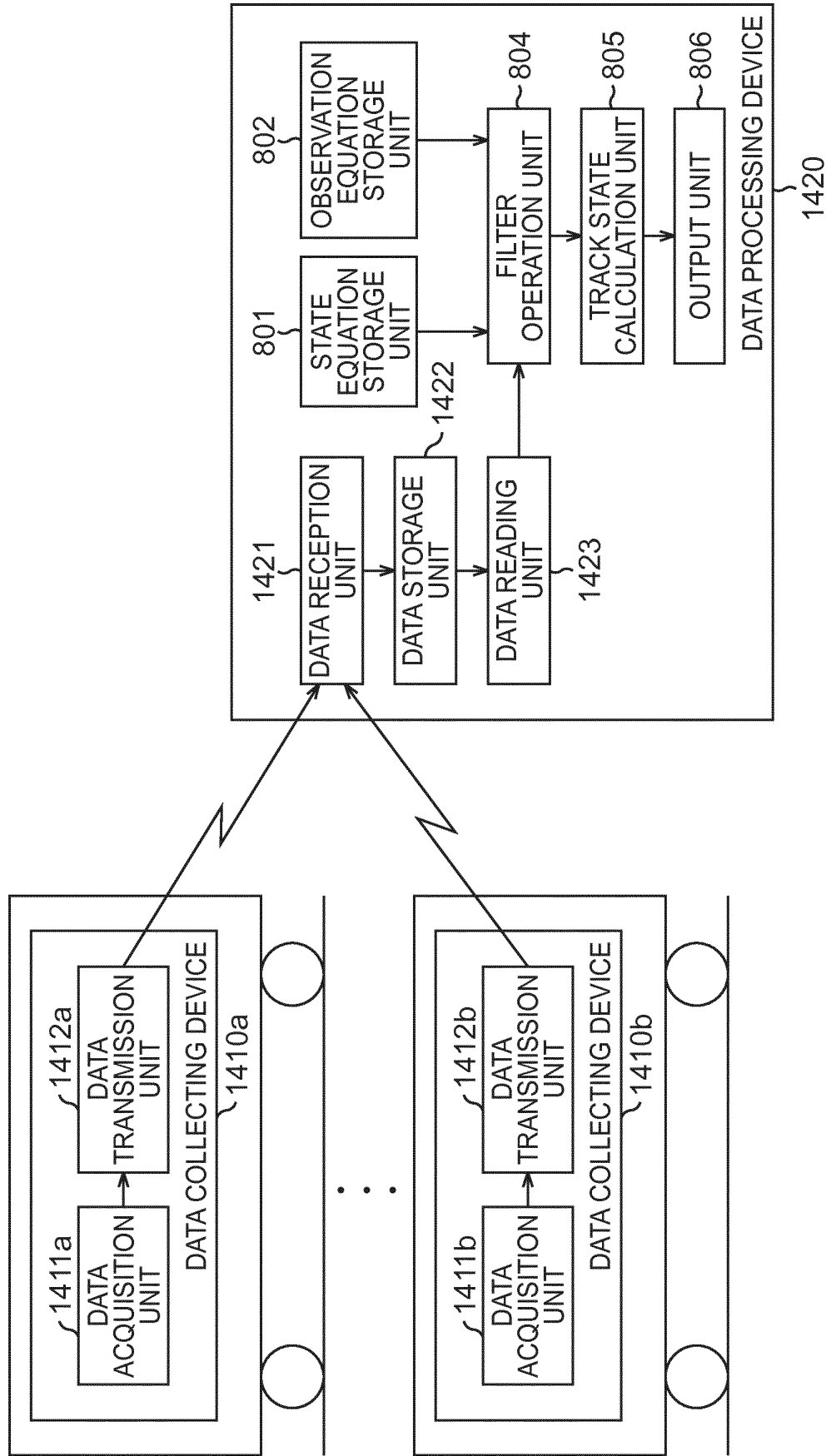


FIG. 14



INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2017/011010

A. CLASSIFICATION OF SUBJECT MATTER

B61K9/08(2006.01)i, B60L3/00(2006.01)i, B61D37/00(2006.01)i, B61F5/24
(2006.01)i, B61L1/20(2006.01)i, E01B35/00(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

B61K9/08, B60L3/00, B61D37/00, B61F5/24, B61L1/20, E01B35/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Jitsuyo Shinan Koho 1922-1996 Jitsuyo Shinan Toroku Koho 1996-2017

Kokai Jitsuyo Shinan Koho 1971-2017 Toroku Jitsuyo Shinan Koho 1994-2017

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2012/0199700 A1 (TECHNISCHE UNIVERSITEIT DELFT), 09 August 2012 (09.08.2012), abstract & WO 2011/019273 A1 & EP 2464555 A1 & NL 2003351 C & AU 2010283066 A1 & CA 2771003 A1 & KR 10-2012-0044378 A & CN 102548828 A & DK 2464555 T3 & ES 2523350 T3	1-16
A	JP 2015-227834 A (The Nippon Signal Co., Ltd.), 17 December 2015 (17.12.2015), paragraph [0022] (Family: none)	1-16

☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search
20 April 2017 (20.04.17)

Date of mailing of the international search report
09 May 2017 (09.05.17)

Name and mailing address of the ISA/
Japan Patent Office
3-4-3, Kasumigaseki, Chiyoda-ku,
Tokyo 100-8915, Japan

Authorized officer

Telephone No.

INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2017/011010

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP 2014-126451 A (Railway Technical Research Institute), 07 July 2014 (07.07.2014), paragraph [0024] (Family: none)	1-16
A	JP 2014-43149 A (Tokyo Keiki Inc.), 13 March 2014 (13.03.2014), paragraph [0046] (Family: none)	1-16

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REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- JP 56019404 A [0004]
- JP 2005067276 A [0004]

Non-patent literature cited in the description

- Railway vehicle dynamics The latest bogie technology. The Japan Society of Mechanical Engineers, January 2003, 15-33 [0005]
- **PING LI et al.** Estimation of railway vehicle suspension parameters for condition monitoring. Control Engineering Practice, 2007, vol. 15, 43-55 [0005]