Robust Resonance Suppression Control based on Self Resonance Cancellation Disturbance Observer and Application to Humanoid Robot

Motonobu Aoki
and Hiroshi Fujimoto
and Yoichi Hori
The University of Tokyo
Tokyo, Japan
Email: http://hflab.k.u-tokyo.ac.jp

Taro Takahashi
Advanced Technology Engineering Department,
Partner Robot Division,
Toyota Motor Corporation
Tokyo, Japan
Email: taro_takahashi@mail.toyota.co.jp

***Abstract*—In this paper, a robust control method for two-inertia systems is proposed based on the Self Resonance Cancellation Control (SRC) and the Self Resonance Cancellation Disturbance Observer (SRCDOB). The SRCDOB proposed in this paper improves the robustness of control system by rejecting disturbances and compensating for deviation of plant dynamics. The feedback controller for two-inertia systems is designed based on a nominalized plant model by SRCDOB and its effectiveness is verified through simulation study. In addition, the proposed robust resonance suppression control method is applied to a humanoid robot control system and experimental results demonstrated the effectiveness of the proposed robust control method.**

I. Introduction

Low birthrate and longevity have been progressing, so humanoid robots have been the focus of attention as the human labor force which can be replaced with people. Recently, improvement in kinematical performance is remarkable through the development of technology. Therefore, it is necessary to model a plant by a two-inertia system, and introduce a resonance suppression control. In the motion control field, many resonance suppression controls such as Notch Filter, Resonance Ratio Control, SRC are proposed, but these methods are not robust for modeling error [1]-[5]. It is difficult to apply these methods for a humanoid robot which changes its dynamics due to the change of inertia moment of inertia, centrifugal force, coriolis force, gravity, frictional force, in accordance with the posture.

On the other hand, Disturbance Observer (DOB) is proposed as a control method which regards all modeling errors as disturbances, nominalizes a plant, and improves the robustness over modeling errors[6][7]. A DOB can nominalize a one-inertia system, but if this method is applied to a two-inertia system, a big vibration is induced according to the elasticity and the load inertia of the transmission.

From the above reason, robust resonance suppression control is required for modelling error of a plant modeled as a two-inertia system, to improve control performance of a humanoid robot. Thus in this paper, a robust resonance suppression control for modelling errors of a two-inertia system is realized for a humanoid robot leg by using both SRC with consideration of the viscosity term of load, and SRCDOB together.

The composition of this paper is shown below. Firstly, the composition of the 3-joint leg robot created for this research is explained. Secondly, the design method of SRC in consideration of the viscosity term of load is stated. Moreover, SRCDOB devised based on the theory of SRC is stated, and this method nominalizes the apparent plant of SRC. Then, it is shown that a robust resonance suppression control for modelling errors of a two-inertia system is realized by using SRC in consideration of the viscosity term of load and SRCDOB together. Finally, both methods are applied to a 3-joint leg robot, and it is shown that the disturbance suppression characteristic and the reference tracking performance of the control method which combines SRC and SRCDOB excels those of the control method which combines PID and DOB.

II. 3-Joint Leg Robot and Modeling in Two-inertia System

A. Basic Composition of 3-Joint Leg Robot

We made 3-Joint leg robot shown in Fig.1 in order to do basic examination of control design in a robot leg. The 3-joint leg robot has hip, knee and ankle joints. Each joint is connected to a harmonic gear through a timing belt from a motor shown in Fig.2. Modeling in two-inertia system for each joint is necessary under the influence of the elasticity of each timing belt. The block diagram for the two inertia system is shown in Fig.3. Motor moment of inertia, motor damping coefficient, load moment of inertia, load damping coefficient and spring constant are denoted respectively as J_M, B_M, J_L, B_L, K, and their nominal values are denoted as J_{Mn}, B_{Mn}, J_{Ln}, B_{Ln}, K_n. Gear ratio is denoted as n. Here after, all variables with subscript n denote nominal values, and motor side angular position is denoted as θ_M, and load side angular position is denoted as θ_L. In this paper, the knee joint is examined among the three.

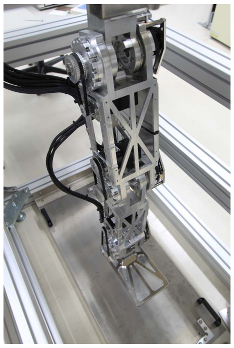

Fig. 1. 3-Joint Leg Robot

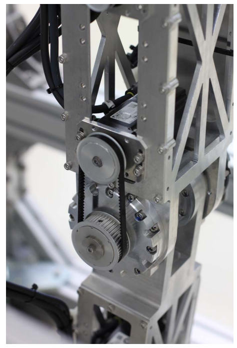

Fig. 2. Composition of Transmission of Joint

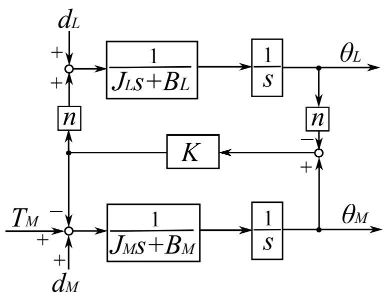

Fig. 3. Block Dyagram of 2-inertia System

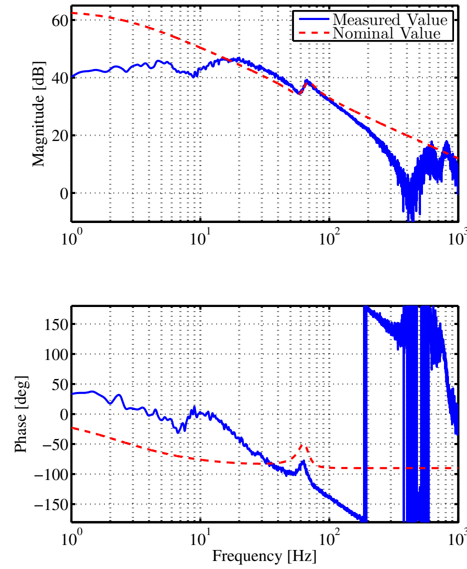

Fig. 4. Bode Diagram for Knee Joint

B. Frequency Responce Characteristic of Knee Joint and its Modeling in Two-inertia System

The bode diagrams of the frequency responce characteristic from motor torque references (T_M) to motor angle (θ_M) for the knee joint and those of two-inertia system fitting model are shown in Fig.4. This frequency characteristic is measured making the thigh and the lower thigh perpendicular to the ground, and the forefoot horizontal to the ground. The resonance at 60 Hz comes from the timing belt. Nominal values decided by this frequency responce characteristic are shown in Table.I. The reason why this model fitting is not done exactly for the gain in the low frequency level, is that gravity influences the robot in low frequency level. This problem is solved by using SRCDOB to state in section III-B.

III. Self Resonance Cancellation Control and Self Resonance Cancelaltion Disturbance Observer

SRC is a resonance cancellation method proposed by Sakata et al[5]. The SRC cancels the resonance of the apparent plant, by using encorders attached at both the motor and the load end, regarding the system as 1I2O one, and feeding back the encorder signals with some gains multiplied. The apparent plant of SRC is mentioned later. SRC design can be done without knowledge of spring constant (K), so it is robust with respect to perturbations in spring constant (K). Also, this method has been applied to a three-inertia system by Shiraishi et al[8]. However, SRC proposed by Sakata et al is stated neglecting the viscosity term, and the design procedure is also complicated. Moreover, because SRC does not take modeling errors into consideration, it is difficult to be applied to a humanoid robot which changes moment of inertia, centrifugal force, coriolis force, gravity, frictional force according to the postual changes. Furthermore, SRC proposed by Sakata et al also has a problem that a steady-state error arises due to load side disturbance torque. In this section, SRC design method solving these problems and SRCDOB method based on the theory of SRC are stated.

TABLE I
Model Parameter

J_{Mn}	[Nm/s^2]	0.00004	J_{Ln}	[Nm/s^2]	0.1
B_{Mn}	[Nm/s]	0.00001	B_{Ln}	[Nm/s]	10
K_n	[N/m]	1.05	n		120

A. Self Resonance Cancellation Control

For a two-inertia system, transter functions from motor torque reference (T_M) to motor anglular position (θ_M), from motor torque reference (T_M) to load angular position (θ_L), from load side disturbance torque (d_L) to motor anglular position (θ_M), from load side disturbance torque (d_L) to load angular position (θ_L) become

$$P_{MM} = \frac{\theta_M}{T_M} = \frac{J_L s^2 + B_L s + K n^2}{D_M} \quad (1)$$

$$P_{LM} = \frac{\theta_L}{T_M} = \frac{Kn}{D_M} \quad (2)$$

$$P_{ML} = \frac{\theta_M}{d_L} = \frac{K}{D_L} \quad (3)$$

$$P_{LL} = \frac{\theta_L}{d_L} = \frac{J_M s^2 + B_M s + K}{D_P} \quad (4)$$

where,

$$
\begin{aligned}
D_M &= J_M J_L s^4 + (J_M B_L + J_L B_M) s^3 \\
&\quad + (n^2 J_M K + J_L K + B_M B_L) s^2 \\
&\quad + (n^2 B_M K + B_L K) s && (5)\\
D_L &= J_M J_L s^4 + (J_M B_L + J_L B_M) s^3 \\
&\quad + \left(J_M K + \frac{J_L K}{n^2} + B_M B_L \right) s^2 \\
&\quad + \left(B_M K + \frac{B_L K}{n^2} \right) s. && (6)
\end{aligned}
$$

In order to take into consideration the viscosity term which was not taken into consideration in the conventional SRC, the block diagram of SRC is redrawn in Fig.5. C_{FB} is the feedback controller which can be designed freely. The difference from the conventional SRC is the point of taking β and δ into consideration.

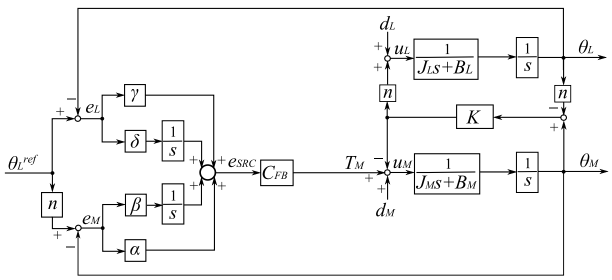

Fig. 5. Block Diagram of SRC

In this case, the nominal transfer functions from load angular position reference (θ_L^{ref}) to actual value (θ_L) is denoted G_{Cn} for closed loop, and G_{On} for open loop, as follows

$$
\begin{aligned}
G_{Cn} &= \frac{P_{LMn} \left\{ n \left(\alpha + \frac{\beta}{s} \right) + \left(\gamma + \frac{\delta}{s} \right) \right\} C_{FB}}{1 + P_{SRCn} C_{FB}} && (7)\\
G_{On} &= P_{SRCn} C_{FB} && (8)
\end{aligned}
$$

where,

$$
P_{SRCn} = P_{MMn} \left(\alpha + \frac{\beta}{s} \right) + P_{LMn} \left(\gamma + \frac{\delta}{s} \right). \quad (9)
$$

Where, the apparent plant of SRC is defined as SRC plant (P_{SRC}). Next, the nominal value of SRC plant (P_{SRCn}) is expressed as

$$
P_{SRCn} = \frac{1}{s^2}. \quad (10)
$$

Normally there are an infinite number of solutions. However, without using K, each parameter can be determined as follows:

$$
\begin{aligned}
\alpha &= J_{Mn} \\
\beta &= B_{Mn} \\
\gamma &= \frac{J_{Ln}}{n} \\
\delta &= \frac{B_{Ln}}{n}.
\end{aligned} \quad (11)
$$

Applying the above parameters, the resonance term of nominal SRC plant (P_{SRCn}) is cancelled out.

Finally, C_{FB} should be designed for nominal SRC plant (P_{SRCn}). Then, using motor angular position error (e_M) and load angular position error (e_L), SRC output angular position error (e_{SRC}) is defined as

$$
e_{SRC} = \left(\alpha + \frac{\beta}{s} \right) e_M + \left(\gamma + \frac{\delta}{s} \right) e_L \quad (12)
$$

which is zeroed by SRC. However, load angular position error (e_L) which should be 0 is not zeroed by it. This problem is solved in section III-C.

B. Self Resonance Cancellation Disturbance Observer

DOB is a control method which nominalizes a one-inertia plant i.e. a plant without resonance terms[6][7]. From equation (10), because nominal SRC plant (P_{SRCn}) does not have resonance terms, it can be expected easily that DOB for two-inertia system is realized if DOB is designed for SRC plant P_{SRC}. Therefore, in this section, the design method of DOB based on the theory of SRC, i.e., SRCDOB design method is stated.

Equation (9) is stated for a nominal value, but modeling errors arise in fact. Therefore SRC plant should be

$$
P_{SRC} = P_{MM} \left(\alpha + \frac{\beta}{s} \right) + P_{LM} \left(\gamma + \frac{\delta}{s} \right). \quad (13)
$$

When both sides are multiplied by $T_M s$,

$$
\begin{aligned}
T_M P_{SRC} s &= T_M \{ P_{MM} (\alpha s + \beta) + P_{LM} (\gamma s + \delta) \} \\
\Leftrightarrow \quad \dot{\theta}_{SRC} &= \alpha \dot{\theta}_M + \beta \theta_M + \gamma \dot{\theta}_L + \delta \theta_L. && (14)
\end{aligned}
$$

Where, SRC output angular position (θ_{SRC}) is defined as

$$
\theta_{SRC} = T_M P_{SRC}. \quad (15)
$$

θ_{SRC} is an angle to use in the theory of SRC, so it is completely different from θ_M and θ_L.

Then, when DOB is constructed using SRC output angular velocity ($\dot{\theta}_{SRC}$), the block diagram is drawn in Fig.6. This method is named SRCDOB. In this case, SRCDOB estimated disturbance ($\hat{d}_{SRC}$) is determined as

$$
\hat{d}_{SRC} = Q \left(T_M - s \dot{\theta}_{SRC} \right). \quad (16)
$$

Taking modelling errors into consideration, SRCDOB estimated disturbance ($\hat{d}_{SRC}$) can be caluculalted as follows.

$$
\begin{aligned}
\hat{d}_{SRC} &= Q T_M \{ \Delta P_{MM} (s\alpha + \beta) + \Delta P_{ML} (s\gamma + \delta) \} \\
&\quad + Q d_M [1 + J_M s \{ \Delta P_{MM} (s\alpha + \beta) + \Delta P_{ML} (s\gamma + \delta) \}] \\
&\quad + Q \tfrac{d_L}{n} [1 + J_M s \{ \Delta P_{LM} (s\alpha + \beta) + \Delta P_{LL} (s\gamma + \delta) \}] && (17)
\end{aligned}
$$

where,

$$
\begin{aligned}
\Delta P_{MM} &= P_{MM} - P_{MMn} \\
\Delta P_{LM} &= P_{LM} - P_{LMn} \\
\Delta P_{ML} &= P_{ML} - P_{MLn} \\
\Delta P_{LL} &= P_{LL} - P_{LLn}.
\end{aligned} \quad (18)
$$

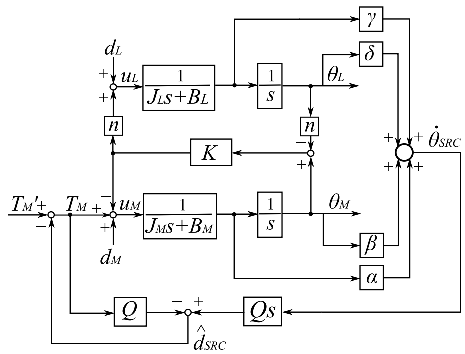

Fig. 6. Block Diagram of SRCDOB

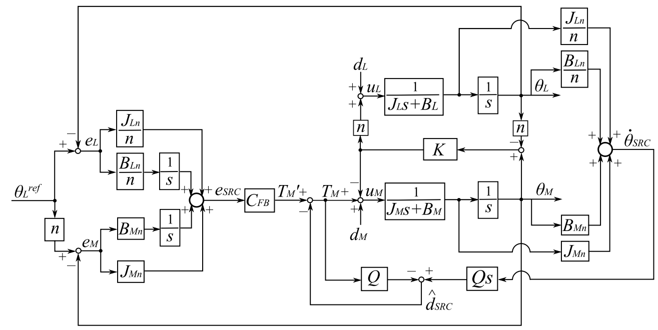

Fig. 7. Block Diagram of SRC with SRCDOB

Moreover, if there is no modeling error, SRCDOB estimated disturbance ($\hat{d}_{SRC}$) is

$$\hat{d}_{SRC} = Q\left(d_M + \frac{d_L}{n}\right). \tag{19}$$

Equation (19) shows that there is no resonance term for SRCDOB estimated disturbance. Therefore, cut-off frequency of the Q filter can be larger than the resonance frequency.

Then, the transfer function from apparent motor torque reference (T'_M) to SRC output angular velocity ($\dot{\theta}_{SRC}$) is caluculated in (20) for $Q \approx 1$,

$$\frac{\dot{\theta}_{SRC}}{T'_M} = \frac{1}{s} = P_{SRCn} s \tag{20}$$

resulting in the same form as the nominal SRC plant (P_{SRCn}) in (10). This shows that a SRC plant (P_{SRC}) is nominalized by SRCDOB. Therefore a robust control system for all parameters e.g. J_M, B_M, J_L, B_L for two-inetia system is composed by combining SRC which is robust for spring constant (K) and SRCDOB which nominalizes the SRC plant (P_{SRC}).

C. Control System Combining Self Resonance Cancellation Control and Self Resonance Cancellation Disturbance Observer

The block diagram of the control system combining SRC and SRCDOB is shown in Fig.7. However, as stated in III-A, SRC output angular position error e_{SRC} is zeroed by SRC, but load angular position error (e_L) which should be zero is not zeroed by it. This is the same in the case of combining SRC and SRCDOB.

In order to solve the problem, if SRC and SRCDOB are designed as $B_{Mn} = 0$ and $B_{Ln} \neq 0$ even in the case of $B_M \neq 0$, the control system with $e_{SRC} \to 0$ and $e_L \to 0$ can be designed, because the number of integrator of the load anglular position error is one larger by one than that of the motor angular position error.

IV. Simulations

In this chapter, the control systen combining PID and DOB, and the control system combining SRC and SRCDOB are compared in simulations. Modelling error is given for load inertia moment of $J_L = 2J_{Ln}$. The poles of each feedback controller are placed to meet the expeirmental stability conditions in section IV-C as the form of multiple roots. The poles (ω_C) of the PID controller are placed at $\omega_C = -30 \times 2\pi$ [rad/sec] as a multiple root for the rigid body of P_{MMn}, while that of the SRC is at $\omega_C = -50 \times \pi$ [rad/sec] as a multiple root for the nominal SRC plant P_{SRCn}.

Moreover, The Q filter transfer function is chosen to be

$$Q = \frac{\omega_Q}{s + \omega_Q}. \tag{21}$$

The Q filter cutoff frequency (ω_Q) of DOB is placed at $\omega_Q = 25 \times 2\pi$ [rad/sec] and that of SRCDOB is placed at $\omega_Q = 600 \times 2\pi$ [rad/sec] to meet the expeirmental stability conditions in section IV-C too.

A. Nominalization of SRC plant (P_{SRC}) by SRCDOB

In this section, it is simulated that SRC plant (P_{SRC}) is nominalized by SRCDOB when modelling error is induced for load inertia moment $J_L = 2J_{Ln}$. The three transfer functions: $1/s^2$; SRC plant (P_{SRC}) when the modelling error exists; and nominalized SRC plant (P_{SRC}) by SRCDOB when the modelling error exists, are shown in Fig.8.

Fig.8 points out that SRC plant (P_{SRC}) is nominalized by SRCDOB and the resonance is almost cancelled in the case which the modelling error is induced for load inertia moment $J_L = 2J_{Ln}$. Because Q is not completely 1, the resonance does not completely disappear. If Q were 1, the resonance would cancelled completely.

B. Sensitivity Function of Control System Combining SRC and SRCDOB

In this section, motor side sensitivity function and load side sensitivity function of the control system combining PID and DOB and the control system combining SRC and SRCDOB are compared in the case which modelling error is induced for load inertia moment $J_L = 2J_{Ln}$. Motor side sensitivity function is determind as the transfer function from motor side disturbance torque (d_M) to motor side input torque u_M, and load side transfer function is determined as the transfer function from load side disturbance torque (d_L) to load side input torque (u_L). Motor side transfer function is shown in Fig.9 and load side transfer function is shown in Fig.10.

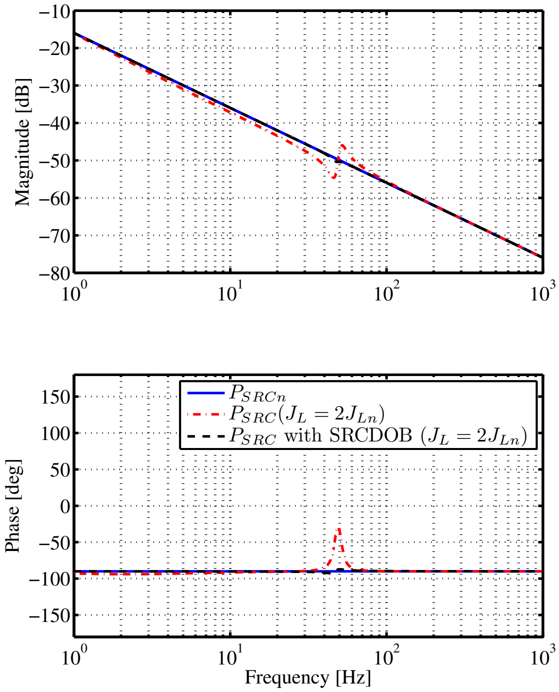

Fig. 8. Bode Plot of P_{SRC}

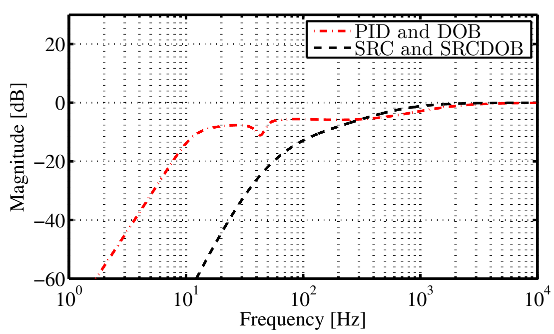

Fig. 9. Motor Side Sensitivity Function

Fig.9 points out that the gain for low frequencies of the control system combining SRC and SRCDOB are smaller than that of the control system combining PID and DOB. Therfore, the control system combining SRC and SRCDOB is more robust for motor side distuebance torque (d_M) than the control system combining PID and DOB.

V. Experiments

In this section, the control systen combining PID and DOB and the control system which combines SRC and SRCDOB are compared in experiments. The poles of controllers and the Q filter cut-off frequencies are same in Section IV.

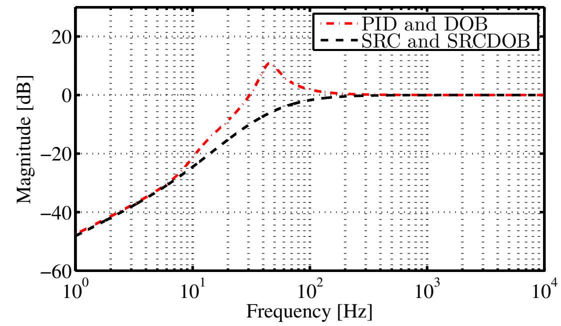

Fig. 10. Load Side Sensitivity Function

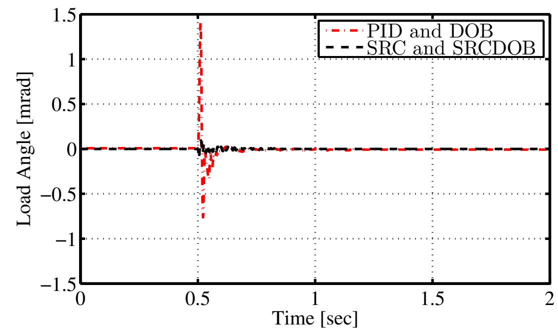

Fig. 11. Motor Side Disturbance Addition Experiment

A. Motor Side Disturbance Torque Addition Experiment

In this section, the control system combining PID and DOB and that of SRC and SRCDOB are compared in motor side distuebance torque suppression efficiency. Motor side disturbance torque is added from software. For both controllers, the load angular position reference is set to 0, and a motor side step disturbance torque 1Nm at time 0.5s is added. The experiment results is shown in Fig.11. Fig11 points out that the control system combining SRC and SRCDOB is suppresed more than the control system combining PID and DOB as same as Fig.9 shows.

B. Load Side Disturbance Torque Addition Experiment

In this section, the control system combining PID and DOB and the control system combining SRC and SRCDOB are compared in load side distuebance torque suppression efficiency. Step input torque is added to the ankle motor in the state which ankle is bent to the mechanical limit, and the reaction torque is regarded as the load side disturbance torque of knee joint. For both controllers, the load angular position refernce is set to 0, and a motor side step disturbance torque for the ankle joint 1Nm at time 0.5s is added. This means that load side torque for ankle joint is 120Nm because the ratio of transmission for the ankle joint is 120.

The experiment results are shown in Fig.12. Because the control system combining PID and DOB does not use load angular position θ_L, a steady-state error arises by load side

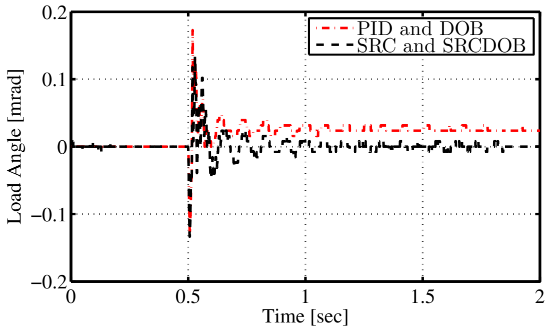

Fig. 12. Load Side Disturbance Addition Experiment

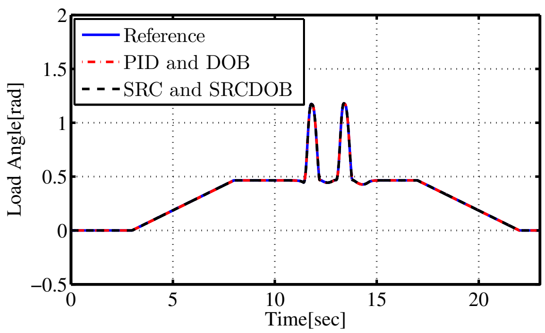

Fig. 13. Orbit Following Experiment

disturbance torque in the control system. However, a steady-state error arises by load side disturbance torque in the control system combining SRC and SRCDOB. The vibration of 12Hz arises for both control systems, but the factor is the resonance of hip joint, and this is not for knee joint controllers.

C. Reference Tracking Experiment

In this section, reference tracking experiments for the control system combining PID and DOB and reference tracking experiment for the control system combining SRC and SRCDOB are compared. The real reference of a humanoid robot's step is used in these experiments. In these simulations, firstly a leg is taken to initial posture and two times of step are performed. Then, the hip joint and the ankle joint move simultaneously, so the reaction torques work as disturbance torque for knee joint. Moreover, the modeling errors is also taken into consideration because a posture change occurs. Time responses of refernce tracking experiments is shown in Fig.13 and the errors with references is shown in Fig.14. Fig.13 and Fig.14 point out the control system combining SRC and SRCDOB has better tracking characteristics than that of the control system combining PID and DOB.

VI. Conclusion

In this paper, the design method of SRC in consideration of the viscosity term of load and SRCDOB design method are stated. Then, Combining these, it is stated that robust resonance suppression control for a two-inertia system is

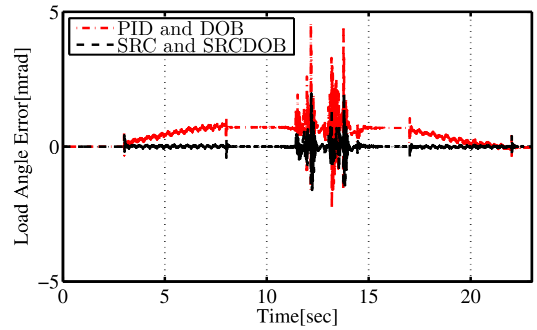

Fig. 14. Orbit Following Experiment (Error)

realized, and this control method is applied for a leg of humanoid robot in simulations and experiments.

The control system combining SRC and SRCDOB is better than the control system combining PID and DOB. In particular, the poles of PID are placed at $\omega_C = -30 \times 2\pi$ [rad/sec], but those of SRC are at $\omega_C = -50 \times 2\pi$ [rad/sec]. Moreover, The Q filter cut-off frequency of DOB is $\omega_Q = 25 \times 2\pi$ [rad/sec], but that of SRCDOB is $\omega_Q = 600 \times 2\pi$ [rad/sec]. Therfore, the disturbance suppression characteristics of motor side and load side for the control system combining SRC and SRCDOB better than the control system combining PID and DOB. Also in refernce tracking experiment, the control system combining SRC and SRCDOB is superior to the control system combining PID and DOB.

The control system combining SRC and SRCDOB proposed in this paper is clear, and this method can be applied for many appllications not only humanoid robot. It would be our pleasure if this paper could be helpful to the study of motion control.

References

[1] Y. Hori, H. Sawada, and Y. Chun: "Slow resonance ratio control for vibration suppression and disturbance rejection in torsional system", IEEE Trans. Ind. Electron., vol. 46, no. 1, pp. 162-168, Feb. 1999.

[2] K. Ohisi, N. Shimada, and T. Miyazaki: "High-performance robot motion control based on zero-phase notch filter for industrial robot", The 11th IEEE International Workshop on Advanced Motion Control, pp.626 - 630, March 21-24, 2010, Nagaoka, Japan

[3] K. Yuki, T. Murakami, and K. Ohnishi:"Vibration Control of a 2 Mass Resonant System by the Resonance Ratio Control", Trans. Inst. Elect. Eng. Jpn. vol.113-D, no. 10, pp. 1162 - 1169, 1993.

[4] Y. Seki, K. Saiki, H. Fujimoto: "Self Resonance Cancellation using Multiple Sensors for Ballscrew Driven Stage", The 12th IEEE International Workshop on Advanced Motion Control, pp.1-6 March 25 - 27, 2012

[5] K. Sakata, H. Fujimoto, and K. Saiki "Optimal mechanical parameter design using Self Resonance Cancellation control for gantry-type high precision stage",to be published in Proc. IEEJ Industry Applications Society Conf. (JIASC 2011), (in Japanese).

[6] K.Ohnishi: "New Development of Servo Technology in Mechatronics", IEEJ Transactions on Industry Applications, vol.107-D, no.1, pp.83-86, 1987. (in Japanese)

[7] T. Umeno and Y. Hori, "Robust speed control of DC servomotors using modern two degrees-of-freedom controller design," IEEE Trans. Ind. Electron., vol. 38, pp. 363-368, Oct. 1991.

[8] T. Shiraishi, H. Fujimoto: "Vibration Suppression Position Control of Three-inertia Systems Using Self Resonance Cancellation Control", in Proc. IEE of Japan Technical Meeting Record, IIC-11-171, 2011 (in Japanese).