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Estimation of Reaction Torque and Compensation for Elongation of Wire for Wire Actuated Robotic Forceps

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Abstract: When a load is added to the tip of a wire actuated robotic forceps, tracking accuracy of the forceps is degraded due to the elastic elongation of the wire. In this paper, for the wire actuated robotic forceps, a new algorithm that can estimate a reaction torque and an amount of elongation of the wire, is proposed. By compensating for amount of elongation of the wire, track ability of the forceps is improved. The effectiveness of the proposed algorithm was verified through simulation and experimental works.

Keywords: Reaction force observer (RFOB), Robotic forceps, Estimation of reaction torque**,** Compensation for elongation of wire, Accuracy of tracking control.

1. INTRODUCTION

Minimally invasive surgery has a characteristic that can reduce a burden of patients. However, it causes difficult operation for surgeons due to the inflexibility of surgical instruments and small work space. Therefore, development of the surgical support devices with the application of robot technology is in demand, e.g. Taylor et al. (2003). Recently, robotic surgical support systems such as 'da Vinci' are in clinical use. In Ishii et al. (2010), we have developed a multi-DOF robotic forceps manipulator for minimally invasive surgery using a novel omnidirectional bending technique with screw drive mechanism termed double-screw-drive (DSD) mechanism, so far.

Many of multi-DOF robotic forceps manipulators used in robotic surgery such as 'da Vinci' are driven by wire actuation. Such multi-DOF robotic forceps manipulators have problems in accuracy of tracking control due to an elastic elongation of the wire. Therefore, many studies have been tried to enhance the track ability of the robotic forceps manipulators. In Ikuta et al. (2006), a compensation algorithm of wire friction was proposed for nine degrees of freedom wire actuated robotic manipulator termed "Hyper Finger" developed in Ikuta et al. (2003) for minimally invasive surgery in deep organs. In Tsukahara et al. (2010), a method to prevent an elongation of a wire was proposed for the forceps with a driving system which combined a motor for force control and a motor for position control by measuring a tension of the wire. Modeling and control of serial elastic actuators and tendon driven robots are addressed in Lens et al. (2013) and Veneman et al. (2005).

On the other hand, in order to improve an operability of the robotic surgical support systems and to help surgeon's dexterity, development of haptic forceps manipulators is required. Most recently, haptic forceps manipulator for minimally invasive surgery has been proposed in Seibold et al. (2005), Zemiti et al. (2007) and Ishii et al. (2011), in which operation force is measured by sensor and force feedback is provided. However, use of the electric sensor in inside of the body is not desirable due to the safety reasons. In addition, the disinfection and sterilization are required for forceps manipulators. Since an autoclave is used for high-pressure steam sterilization, use of the electric sensor is not preferable. Therefore, establishment of a sensorless estimation of the operation force which is added on forceps manipulators is great contribution in the field of robotic surgery. The disturbance observer (DOB) or reaction force observer (RFOB) can estimate a disturbance/reaction force imposed to systems, e.g. Murakami et al. (1993) and Ohnishi et al. (1996). In Ohnishi et al. (2004), using the RFOB, estimation of a reaction force at the tip of a wire actuated forceps has been studied. However, the reaction force cannot be estimated correctly by the conventional RFOB in the case where an elongation of the wire occurred. To the best of our knowledge, estimation of the reaction force for wire actuated forceps with elongation of the wire has not been studied yet.

In this paper, in the case where an elongation of the wire occurred due to a load added to the tip of a wire actuated forceps, a new algorithm that can estimate a reaction torque and an amount of elongation of the wire, is proposed. By compensating for the elongation of the wire using the estimated amount of elongation of the wire, a track ability of the forceps can be improved. In order to demonstrate the validity of the proposed new algorithm, simulation and experimental works were carried out for a simplified wire actuated forceps model. The results showed the effectiveness of the proposed algorithm.

2. ROBOTIC FORCEPS

The robotic forceps incorporating the screwdrive mechanism, termed double-screw-drive (DSD) mechanism, (DSD forceps) is shown in Fig. 1.

The DSD mechanism has three linkages. Two linkages, each consisting of a universal joint of the screwdrive and a spline nut, are for achieving omnidirectional bending motion. A third linkage is for achieving rotary motion of the gripper.

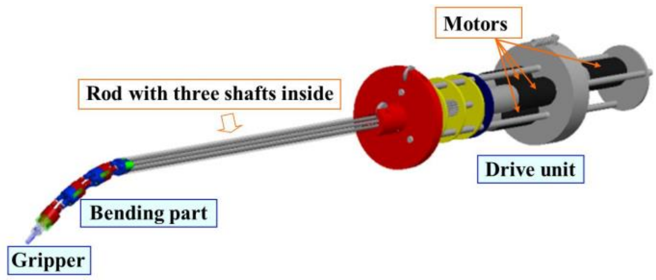


Fig. 1. Overview of DSD forceps

Opening and closing motions of the gripper are attained by wire actuation. Only one side of the jaws can move, and the other side is fixed. The wire for actuation connects to the drive unit through the inside of the DSD mechanism and the rod, and is pulled by the motor. The closed and open states of the gripper are shown in Fig. 2.

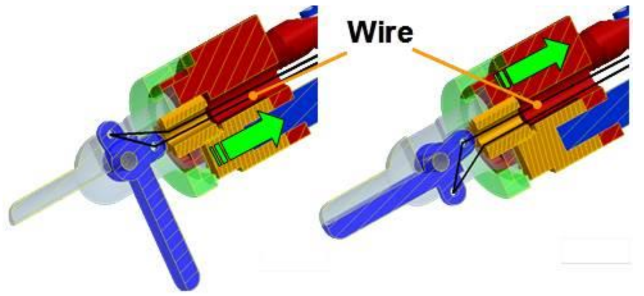


Fig. 2. Open and closed states of the gripper

The built DSD forceps and its controller are shown in Fig. 3. The main specifications of the DSD forceps and the detailed explanation for the mechanism are illustrated in Ishii et al. (2010).

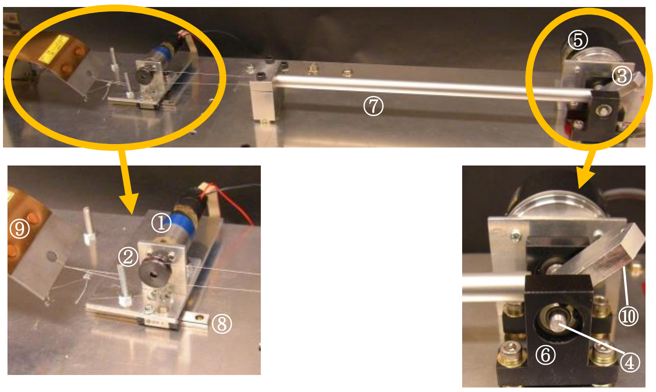
Fig. 3. Built DSD forceps and its controller

3. SIMPLIFIED MODEL

As shown in Fig. 2, wire actuation mechanism is employed for opening and closing motions of the jaw. Then, to detect the grasping force of the jaw without using sensor is desired. In order to analyze the wire actuation mechanism, an enlarged model of one side of the jaw was built and a simplified wire actuated forceps model is introduced. Derivation of a new algorithm based on the RFOB is developed for the simplified model.

3.1 *Enlarged Model of the Jaw*

The built enlarged model of the jaw is shown in Fig. 4. A DC motor rotates a motor pulley. The motor pulley and a joint coupling are connected by a wire passing through the inside of a rod. The jaw is attached to the joint coupling. Then, when the wire is pushed / pulled by rotation of the motor pulley, the jaw closes / opens. A base of the DC motor can move forward and backward on a guide rail. The base is pulled by constant tension by means of a constant load spring so that the wire may not slacken.



① DC Motor ② Motor pulley ③ Jaw ④ Joint coupling ⑤ Rotary encoder ⑥ Joint bearing ⑦ Rod ⑧ Guide rail ⑨ Constant load spring ⑩ Strain gauge

Fig. 4. Enlarged jaw model of wire actuated forceps

In order to compare the estimated reaction torque with the real reaction torque when a load is added to the jaw, a strain gauge was attached to the back side of the jaw. In addition, a rotary encoder was attached to the joint coupling to compare the tracking error of the opening and closing angle of the jaw in case with the wire compensation and without the wire compensation. Note that the strain gauge and the rotary encoder cannot be attached around the jaw of real DSD forceps. These were attached for the purpose of verification.

The specification of the wire used in the enlarged model is shown in Table 1.

Table 1. Specification of wire

Composition	7×7
Material	SUS304
Diameter of wire	0.27 mm
Destruction load	59 N

A simplified model of wire actuated forceps is shown in Fig. 5, where I_M is a moment of inertia of the motor pulley, ϕ_M is a rotation angle of the motor pulley, R is a radius of the motor pulley, f is a tension of the wire, k is a coefficient of elasticity of the wire, x is an amount of elongation of the wire, I_J is a moment of inertia of the joint bearing, θ_J is a rotation angle of the joint bearing, r_J is a radius of the joint bearing, τ_w is a reaction torque and τ_{cJ} is a torque caused by coulomb friction of the joint bearing. It should be noted that θ_J is not measurable in the real DSD forceps, although ϕ_M is measurable.

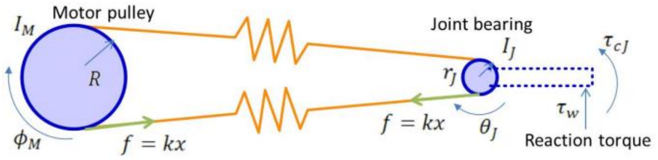


Fig. 5. Simplified model of wire actuated forceps

Equations of motion for the motor pulley part and joint bearing part are given as follows.

$$I_M\ddot{\phi}_M = \tau_m - D\dot{\phi}_m - \tau_F - \tau_{int} - Rkx, \tag{1}$$

$$I_J\ddot{\theta}_J = r_J kx - \{\tau_{cJ} + \tau_w\}, \tag{2}$$

where τ_m is a motor torque, D is a viscosity coefficient, τ_F is a torque caused by coulomb friction of the motor pulley and τ_{int} is a torque caused by internal interference force such as centrifugal force.

3.2 Problem of the Conventional RFOB

If the elongation of the wire is disregarded, the following equation holds.

$$R\phi_M = r_J\theta_J \tag{3}$$

In practice, however, the wire causes elastic deformation when a load is added. Therefore, there exists an elongation in the actual wire. In this case, the amount of elongation of the wire x is given as follows.

$$x = R\phi_M - r_J\theta_J \tag{4}$$

Thus, the following equation holds.

$$\ddot{x} = R\ddot{\phi}_M - r_J\ddot{\theta}_J \tag{5}$$

From (1), (2) and (5), the following equation is derived.

$$\left(I_M + \frac{R^2}{r_J^2}I_J\right)\ddot{\phi}_M =$$
$$\tau_m - \left\{\frac{R}{r_J}\tau_{cJ} + \frac{R}{r_J}\left(\tau_w - \frac{I_J}{r_J}\ddot{x}\right) + D\omega + \tau_F + \tau_{int}\right\} \tag{6}$$

Define $I = I_M + \frac{R^2}{r_J^2}I_J$ and $\tau_l{}' = \frac{R}{r_J}\tau_{cJ} + \frac{R}{r_J}\left(\tau_w - \frac{I_J}{r_J}\ddot{x}\right) + D\dot{\phi}_m + \tau_F + \tau_{int}$. Then, (6) is rewritten as follows.

$$I\ddot{\phi}_M = \tau_m - \tau_l{}' \tag{7}$$

In order to estimate a reaction torque, as shown in Fig. 6, consider to apply the conventional RFOB addressed in Ohnishi et al. (1996) to (7), where I_a^{ref} is a current level reference, K_t is a real value of torque coefficient, K_{tn} is a nominal value of torque coefficient, I_n is a nominal value of moment of inertia I and g_r is a value of the cutoff frequency of lowpass filter. Basic idea of the RFOB is to estimate an external torque from the difference between the input torque to the motor and the output torque which is obtained from the real machine.

In this case, a torque $\frac{R}{r_J}\left(\hat{\tau}_w - \frac{I_J}{r_J}\hat{\ddot{x}}\right)$ is estimated. In the case where the elongation of the wire is disregarded, namely $x = 0$ ($\ddot{x} = 0$), the reaction torque $\hat{\tau}_w$ can be obtained. However, in the case where the elongation of the wire exists, the reaction torque $\hat{\tau}_w$ cannot be obtained using the conventional RFOB, since the acceleration of the elongation of the wire $\ddot{x}$ is unknown.

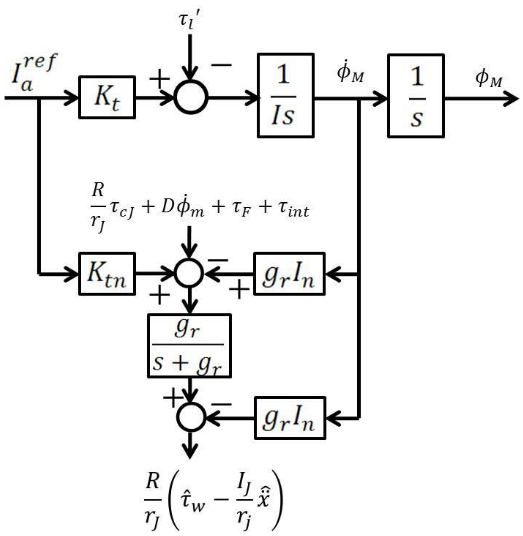


Fig. 6. Block diagram of the conventional RFOB

3.3 Compensation for elongation of the wire

The opening and closing angle of the jaw is controlled based on the measured value of the rotary encoder attached to the driving DC motor. Let θ_J^{ref} denote a target rotation angle of the joint bearing and ϕ_M^{ref} denote a rotation angle of the motor pulley which is required to make the angle of the joint bearing reach the target rotation angle.

If the elongation of the wire is disregarded, ϕ_M^{ref} is given as follows.

$$\phi_M^{ref} = \frac{r_J\theta_J^{ref}}{R} \tag{8}$$

However, since there exists the elongation of the wire, extra rotation of the motor pulley is required to compensate the amount of elongation of the wire. Then, for the amount of elongation of the wire x, required rotation angle of the motor pulley is given by the following equation.

$$\phi_M^{ref} = \frac{r_J\theta_J^{ref} + x}{R} \tag{9}$$

Therefore, in order to compensate the elongation of the wire, it is necessary to estimate the amount of elongation of the wire.

4. ESTIMATION OF REACTION TORQUE AND COMPENSATION FOR ELONGATION OF WIRE

4.1 Estimation of a reaction torque

As shown in Fig. 7, instead of estimating a reaction torque directly, consider to estimate a tension of the wire $\hat{f}$ using the RFOB, where $\tau_l = D\dot{\phi}_m + \tau_F + \tau_{int} + Rkx$.

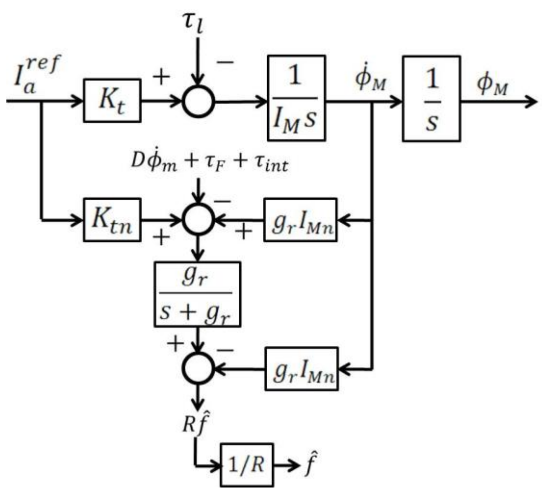


Fig. 7. Estimation of tension of wire

From (1), (2) and (5), the following differential equation about the elongation of the wire x, is derived.

$$\ddot{x} + k\left(\frac{R^2}{I_M} + \frac{r_J^2}{I_J}\right)x = \frac{R}{I_M}\{\tau_m - D\dot{\phi}_m - \tau_F - \tau_{int}\} + \frac{r_J}{I_J}\{\tau_{cJ} + \tau_w\} \tag{10}$$

The differential equation (10) is difficult to solve analytically, since the terms τ_m and τ_w are time variant. Therefore, in this study, it is assumed that the torque fluctuations are small, and operating torques are regarded as constant. Hence, the differential equation (10) is evaluated in the stationary state. Then, analytical solution x_s of the nonhomogenous equation (10) is given as follows.

$$x_s = \frac{\frac{R}{I_M}(\tau_m - D\dot{\phi}_m - \tau_F - \tau_{int}) + \frac{r_J}{I_J}(\tau_{cJ} + \tau_w)}{k\left(\frac{R^2}{I_M} + \frac{r_J^2}{I_J}\right)} \tag{11}$$

In (11), only x_s and τ_w are unknown. Other terms are known by measurement or can be determined through identification experiments.

Multiplying k to both sides of (11) and noting $f = kx$, by substituting the estimated tension of the wire $\hat{f}$ into kx_s, the following equation is derived.

$$\hat{\tau}_w = \hat{f}\left(\frac{R^2}{r_J}\frac{I_J}{I_M} + r_J\right) - \tau_{cJ} - \frac{R}{r_J}\frac{I_J}{I_M}\{\tau_m - D\dot{\phi}_m - \tau_F - \tau_{int}\} \tag{12}$$

Thus, estimation of the reaction torque $\hat{\tau}_w$ is obtained.

4.2 Compensation for elongation of the wire

By substituting the estimated reaction torque $\hat{\tau}_w$ into (11), (11) is rewritten as follows.

$$\hat{x} = \frac{\frac{R}{I_M}(\tau_m - D\dot{\phi}_m - \tau_F - \tau_{int}) + \frac{r_J}{I_J}(\tau_{cJ} + \hat{\tau}_w)}{k\left(\frac{R^2}{I_M} + \frac{r_J^2}{I_J}\right)} \tag{13}$$

Thus, estimation of the amount of elongation of the wire $\hat{x}$ is obtained.

By substituting the estimated amount of elongation of the wire $\hat{x}$ into (9), the target rotation angle of the motor pulley is given as follows.

$$\phi_M^{ref} = \frac{r_J\theta_J^{ref} + \hat{x}}{R} \tag{14}$$

4.3 Algorithm

The proposed reaction torque estimation and elongated wire compensation algorithm is summarised as follows.

(i) Estimate a tension of the wire $\hat{f}$ using the RFOB.

(ii) In the differential equation about the elongation of the wire given by (10), assuming small torque fluctuations, consider an analytical solution x_s given by (11) in the stationary state.

(iii) Substitute the estimated tension of the wire $\hat{f}$ into (12), then estimation of a reaction torque $\hat{\tau}_w$ is obtained.

(iv) Substitute the estimated reaction torque $\hat{\tau}_w$ into (11), then estimation of an amount of elongation of the wire $\hat{x}$ is obtained.

(v) Substitute the estimated amount of elongation of the wire $\hat{x}$ into (9), then the target rotation angle of the motor pulley is given by (14). Compensate for the elongation of the wire using (14) to improve the track ability of the forceps.

5. SIMULATION AND EXPERIMENT

In order to demonstrate the validity of the proposed algorithm, simulation and experimental works were carried out for the simplified wire actuated forceps model. Since the difference of a real value and a nominal value of the parameters and internal interference force are small, they shall be disregarded. Therefore, the following approximation is adopted; $I_M \approx I_{Mn}$, $K_t \approx K_{tn}$ and $\tau_{int} \approx 0$. Parameters used in the simulation and experimental works are shown in Table 2. Parameters k, τ_{cJ}, D and τ_F were determined through parameter identifying experiments.

Table 2. Parameters

R	6.50×10^{-3} m
r_J	2.54×10^{-3} m
I_M, I_{Mn}	3.14×10^{-7} kgm^2
I_J	2.28×10^{-7} kgm^2
K_t, K_{tn}	1.36×10^{-2} Nm/A
g_r	30 Hz
k	2.60×10^{4} N/m
τ_{cJ}	1.91×10^{-2} Nm
D	1.05×10^{-3} kgm$^2/s$
τ_F	5.21×10^{-4} Nm
τ_{int}	0 Nm

5.1 Compensation for elongation of the wire for known load

First, when a known load was added to the jaw, the case where compensation for elongation of the wire was performed was compared with the case where compensation for elongation of the wire is not performed. Four kinds of loads, namely 0 g, 50 g, 100 g, and 150 g, were added to the jaw. The target rotation angle of the jaw θ_J^{ref} was set as 90 degrees. In case where compensation for elongation of the wire was not carried out, tracking control which follows the rotation angle of the motor pulley ϕ_M^{ref} given by (8) was performed, and in case where compensation for elongation of the wire was carried out, tracking control which follows the rotation angle of the motor pulley ϕ_M^{ref} given by (9) was performed. The PID controller was used in the tracking control.

In case where the load added to the jaw is previously known, the amount of elongation of the wire can be calculated by (13). The target angle was set up to increase gradually after starting the experiment and to become 90 degrees in 2 seconds. In addition, the load added to the jaw was also set up to increase constantly after starting the experiment and to become the specified value in 2 seconds. Experiments were executed for the enlarged model of the jaw under the above conditions. Experimental results are shown in Fig. 8.

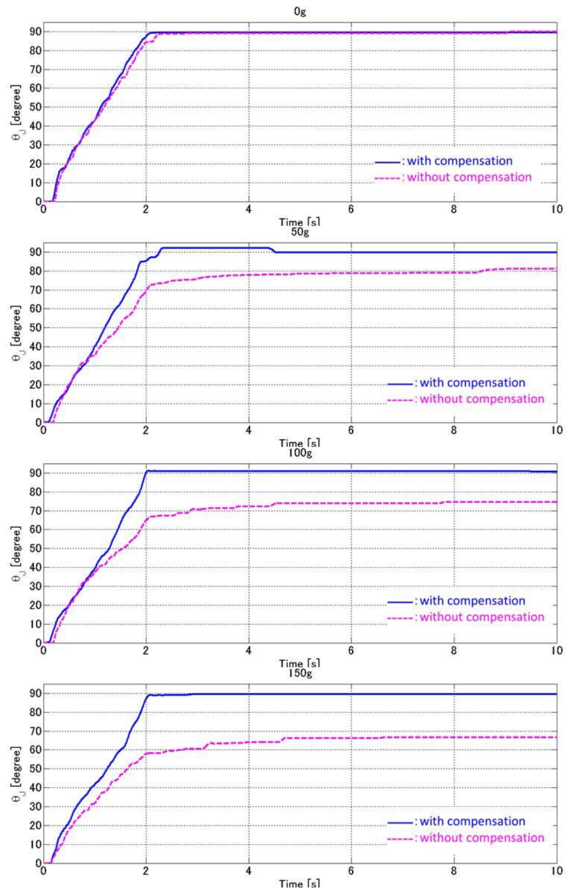


Fig. 8. Experimental results under known load

Fig. 8 shows the rotation angle of the joint bearing, namely rotation angle of the jaw. Solid line shows the result with compensation and broken line shows the result without compensation. In the case where compensation for elongation of the wire was not carried out, the rotation angle did not achieve the target rotation angle. While, in the case where compensation for elongation of the wire was carried out, the rotation angle achieved the target rotation angle. It should be stated that the same results were obtained in the simulation. Thus, the validity of the compensation for elongation of the wire was verified.

5.2 Estimation of reaction torque and compensation for elongation of the wire

Next, using the algorithm given in Section *4.3*, the case where compensation for elongation of the wire based on the estimated reaction torque was performed was compared with the case where compensation for elongation of the wire is not performed. To the first, the loads added to the jaw were estimated, since they were regarded as unknown. However, in practice, four kinds of loads, namely 0 g, 50 g, 100 g, and 150 g, were added. The target rotation angle of the jaw θ_J^{ref} was set as 90 degrees. Other simulation and experimental conditions are the same as explained in Section *5.1*.

(a) Simulation

Simulation result when the 50 g load was added is shown in Fig. 9.

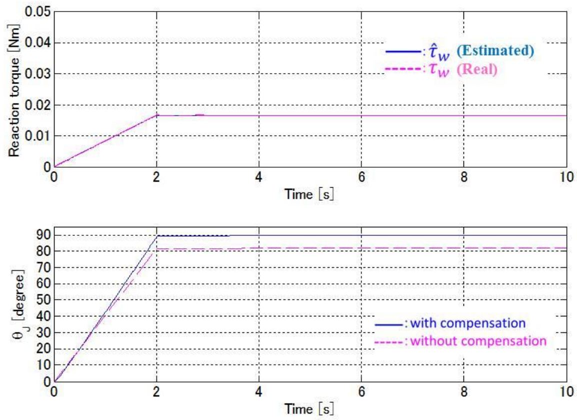


Fig. 9. Simulation result in case of 50 g load

In the upper figure, solid line shows the estimated reaction torque and broken line shows the real reaction torque. In the lower figure, solid line shows the result with compensation and broken line shows the result without compensation. From the results, the reaction torque was estimated as the same value as the actual reaction torque. In addition, the rotation angle of the jaw achieved the target rotation angle by the compensation for elongation of the wire based on the estimated reaction torque. Thus, the effectiveness of the proposed reaction torque estimation and elongated wire compensation algorithm was verified.

(b) Experiment

Experiments were executed for the enlarged model of the jaw, under the same conditions as simulation. Experimental result when the 50 g load was added is shown in Fig. 10.

In the upper figure, solid line shows the estimated reaction torque and broken line shows the reaction torque measured by the strain gauge. In the lower figure, solid line shows the result with compensation and broken line shows the result without compensation. In the experiment, although the reaction torque was approximately estimated, it was vibrating and was estimated larger than the actual reaction torque. In addition, although the rotation angle of the jaw in the case with compensation tracks the target rotation angle well compared with the case without compensation, some steady state deviation was observed. The same tendency has been observed for other loads, namely 0 g, 100 g, and 150 g.

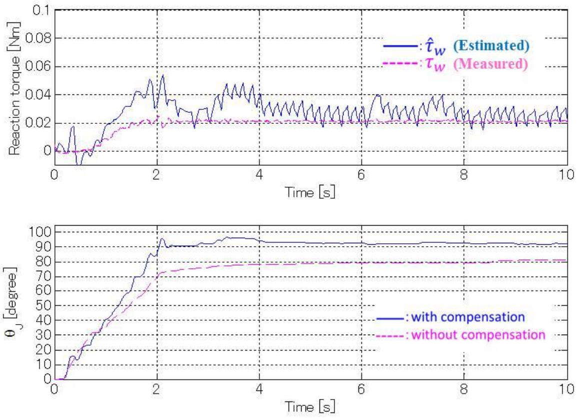


Fig. 10. Experimental result in case of 50 g load

5.3 Consideration

In the simulation, the reaction torque was estimated with sufficient accuracy and elongation of the wire was also compensated correctly. However, in the experiment, the estimated reaction torque was vibrating and was estimated larger than the actual value. With this algorithm, the stationary state is assumed. However, in the experiment, estimation algorithm of the reaction torque is greatly influenced by behavior of the motor, and by the time settling into the stationary state, the estimated reaction torque is changed sharply. For this reason, the estimated reaction torque is considered to become vibrational.

The amount of compensation in the compensation algorithm for elongation of the wire is determined based on the value of the estimated reaction torque. For this reason, when the reaction torque is estimated larger than the actual value, the amount of compensation becomes also large. Therefore, the rotation angle of the jaw is considered to become larger than the target rotation angle.

6. CONCLUSIONS

In this paper, in order to enhance a track ability of the tip motion of a wire actuated forceps, a new algorithm that can estimate a reaction torque and an amount of elongation of the wire, was proposed. In addition, compensation for elongation of the wire was performed based on the estimated amount of elongation of the wire. To demonstrate the validity of the proposed algorithm, simulation and experimental works were carried out for a simplified wire actuated forceps model. The results showed the effectiveness of the proposed algorithm. However, in the experiment, the estimated reaction torque was vibrational and became larger than the actual value. Improvement of the estimation algorithm of the reaction torque to enhance the estimation accuracy is left as a future work.

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