Basic Consideration on Robotic Food Handling by Using Burger Model

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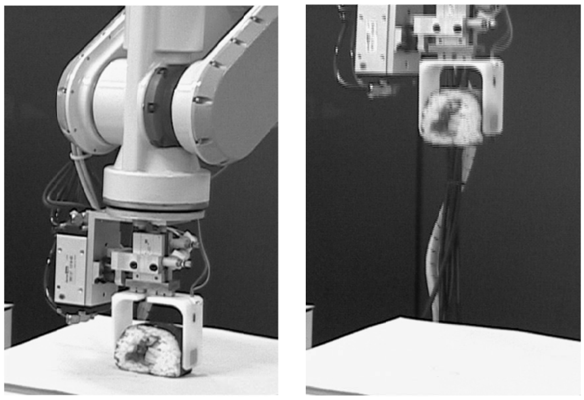
Abstract - This paper discusses a design approach on robotic food handling by considering the characteristics of viscoelasticity. We pick up Norimaki as a typical example with the viscoelastic characteristics. We first show that the dynamic characteristics of Norimaki can be expressed by utilizing the Burger model. After testing the parameter sensitivity, we show an example of the optimum design for determining the combination of the hand stiffness and the operating velocity. We further show that the resultant plastic deformation can be formulated with the exact solution.

Keywords - Food Handling, Viscoelasticity, Burger Model



(a) Gripping motion (b) Lifting motion

Fig. 1. An example of robotic food handling.

1. Introduction

At present, dishing up food into a box lunch sold at convenience stores is done manually by workers standing on both sides of a belt conveyor. The net profit of an individual box lunch, that is, the sales price minus the cost of the raw food materials, personnel expenses and other management costs, is limited to roughly 2% of the retail store price. In order to increase the net profit or to improve the profit ratio for dealing with box lunches, the manual processes for dishing up should be shifted to an automatic sorting and filling system. When designing a robotic hand for handling food, compared to a robotic hand for industrial applications, the viscoelasticity, adhesiveness, and non-homogeneity of objects have to be considered. In this work, we focus on the viscoelasticity of the handling objects and pick up the vinegared rice rolled in laver, so called Norimaki-sushi (or Norimaki), as shown in Fig.1. Handling such a viscoelastic object by a robotic hand can be classified into three phases; the closing phase where the hand base position closes for increasing the grasping force applied to the object, as shown in Fig.2(i), the stationary phase where the hand base position is fixed and the grasping force decreases by the plastic deformation of the object, as shown in Fig.2(ii), and the opening phase where the hand base position opens for releasing the object, as shown in Fig.2(iii). Through all phases, the grasping force f changes with respect to time. The grasping force also changes with the stiffness of the hand. On the other hand, in order to design a robotic hand in dishing up food for box lunches, there are a couple of requirements, including a) lying a total working time cycle T of the robot system within a remunerative time period, b) holding up the object for a prescribed time period T_l for transporting the object, and c) restraining the plastic deformation of object X_p within an acceptable range to ensure product quality. d) keeping an appropriate hand stiffness for the safety in the mechanical strength. Taking the above requirements and the characteristics of object into account, we have discussed a design approach on robotic handling for a viscoelastic object based on the Maxwell model, in our former work [1]. In this work, we utilize the Burger model (four-element model) in analysis of dynamic behaviors of the handled object, since we can more intuitively understand the physical meaning of contact force transition between the hand and the object with the experimental data of Norimaki.

After obtaining the viscoelastic parameters of Norimaki based on the Burger model through experiments, we explore how the parameters effect on handling the object. We then discuss a design approach for robotic hands by considering the characteristics of viscoelasticity and find an optimum set of design parameters. We further discuss that the Burger model has an advantage where the resultant plastic deformation X_p can be computed within a limited time interval.

This paper is organized as follows; In Section 2, we briefly review related works. In Section 3, we obtain the

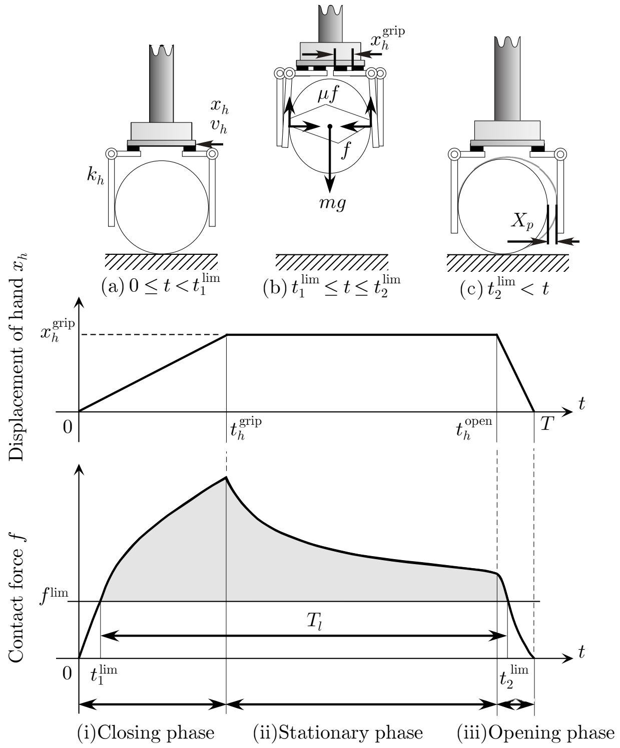


Fig. 2. Three phases for handling a food.

viscoelastic parameters of Norimaki through experiments, and give discussion on the parameter sensitivity. In Section 4, we perform simulations and obtain the optimum combination of the hand stiffness and the operating velocity so that the plastic deformation results in minimum. In Section 5, we discuss an advantage in computing the plastic deformation of object. In Section 6, we give the conclusion of this paper.

2. Related Works

Robotic systems and automations for food processing have been desired by the food industry for a long time. As for deformations of food, Tokumoto *et al.* [2] have shown that a proper combination of both elastic and viscous elements can express the basic behavior of rheology objects. They have also shown simulation results for confirming the validity of the model. As for food handling robots, Li and Lee [3] have developed a visually guided robotic system for handling food. They have shown that the gripper grasps robustly non-homogeneity food by visual information. Silsoe Research Institute [4] has developed the robot hand capable of handling for a food which has adhesion. The hand is composed of a pair of gripping finger and a film like a kind of belt conveyor, can release the adhesion object accurately. Sakamoto *et al.* [1] have discussed a design approach for food handling robot based on the Maxwell model. Also, as for handling soft objects other than food, Taylor [5] have discussed the automatic handling for shoes and garment. Hirai *et al.* [6] have discussed the strategy for handling thin deformable objects such as sheets metal or leather products. Wada *et al.* [7] have proposed the control method for textile fabrics, where the position, posture, and deformation of an object can be controlled by utilizing a vision sensor capable of detecting the position of representative predetermined points on the object. Zheng *et al.* [8] have discussed how to set up a flexible beam with mounting holes in order to automatic assembly tasks.

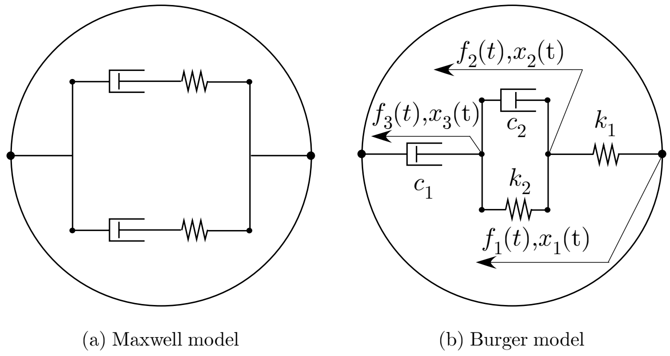


Fig. 3. Two viscoelastic model for approximating a food.

3. Dynamic Characteristic of Food

3.1. General Concept

In general, it is well known that food has rheological characteristics which can be well approximated by dynamic models using elastic and viscous elements, as shown in Fig.3 [9]. While a Maxwell model as shown in Fig.3(a) is applied to approximate characteristic of stress relaxation, each serial viscoelastic unit has a different relaxation time constant. Our former work [1] shows that it can nicely approximate the relaxation curve, by utilizing the four-element Maxwell model with two parallel units where each unit is a serial elastic element and a viscous element, as shown in Fig.3(a). While the same unit is utilized in parallel, it is often the case where the estimated values have much different each other. It is hard for us to find a clear physical reason. In this work, we discuss food handling by using the Burger model as shown in Fig.3(b). The Burger model is composed of one viscous element c_1 and one elastic element k_1 and one unit which is composed of one viscous element c_2 and one elastic element k_2 respectively. We can consider that single viscous element c_1 expresses the permanent plastic deformation, and the elastic element expresses instantaneous deformation. Thus, we can understand intuitively the physical meaning of each viscous and elastic element. We would note that both the Burger and the Maxwell models are equivalent each other when those models have same number of viscous and elastic elements [9].

Now, let us consider that an external force f acts on the object as shown in Fig.3(b), where x, x_i, and f_i are the whole deformation of the object, the deformation and the force where the single elastic element($i = 1$), the parallel viscoelastic unit($i = 2$), the single viscous element($i = 3$), respectively. We would note that we focus on the normal component of force. By the relationship between the force and the displacement in each element, we can obtain the following equations:

$$f(t) = f_i(t), \quad (1)$$

$$x(t) = \sum_{i=1}^{3} x_i(t), \quad (2)$$

$$f_1(t) = k_1 x_1(t), \quad (3)$$

$$f_2(t) = k_2 x_2(t) + c_2 \dot{x}_2(t), \quad (4)$$

$$f_3(t) = c_1 \dot{x}_3(t). \quad (5)$$

By removing f_i and x_i from Eqs.(1)–(5), we can derive the following equation:

$$b_2 \ddot{x}(t) + b_1 \dot{x}(t) = a_2 \ddot{f}(t) + a_1 \dot{f}(t) + f(t), \quad (6)$$

where

$$b_2 \triangleq \frac{c_1 c_2}{k_2}, \quad (7)$$

$$b_1 \triangleq c_1, \quad (8)$$

$$a_2 \triangleq \frac{c_1 c_2}{k_1 k_2}, \quad (9)$$

$$a_1 \triangleq \frac{c_1 k_1 + c_1 k_2 + c_2 k_1}{k_1 k_2}. \quad (10)$$

Equation (6) is the differential equation expressing the relationship between the external force applied to the object f and the deformation x of the object.

3.2. How to Estimate Parameters of Norimaki based on the Burger model

Suppose that an object is grasped by a hand with the stiffness of k_h, as shown in Fig.2. By letting x_h be the displacement of the base of hand, we obtain

$$x(t) = x_h(t) - \frac{f(t)}{k_h}. \quad (11)$$

From Eqs.(6) and (11), we can obtain

$$B_2 \ddot{x}_h(t) + B_1 \dot{x}_h(t) = A_2 \ddot{f}(t) + A_1 \dot{f}(t) + f(t), \quad (12)$$

where

$$B_2 \triangleq \frac{c_1 c_2}{k_2}, \quad (13)$$

$$B_1 \triangleq c_1, \quad (14)$$

$$A_2 \triangleq \frac{c_1 c_2 (k_1 + k_h)}{k_1 k_2 k_h}, \quad (15)$$

$$A_1 \triangleq \frac{c_1 k_1 k_2 + k_h (k_1 c_2 + k_1 c_1 + k_2 c_1)}{k_1 k_2 k_h}. \quad (16)$$

We would now note that Eq.(12) is equivalent to the equation of motion obtained by utilizing the Maxwell model [1], while the parameter distribution for four elements k_1, k_2, c_1, and c_2 are different between them. Based on Eq.(12), we can compute the viscoelastic parameters c_i and k_i of Norimaki from experimental results. Now, suppose that the hand makes contact with the object. The contact force is zero at the initial phase ($t = 0$, $x_h = 0$). We give the commands for open and close to the hand in the following procedure:

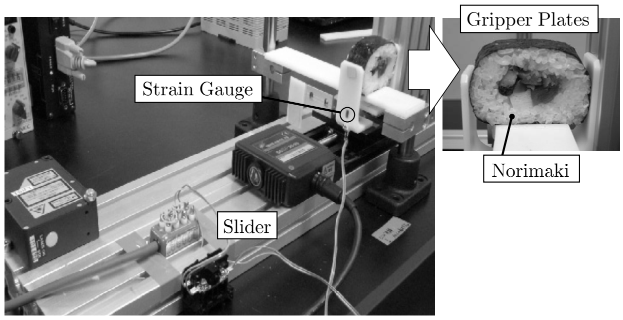


Fig. 4. Experimental system.

1. Closing phase ($0 \le t < t_h^{\mathrm{grip}}$) : Close the hand until the position of x_h results in x_h^{grip} with the operating velocity of $v_h (= \dot{x}_h)$, as shown in Fig.2(i).
2. Stationary phase ($t_h^{\mathrm{grip}} \le t < t_h^{\mathrm{open}}$) : Fix the hand at $x_h = x_h^{\mathrm{grip}}$, as shown in Fig.2(ii).
3. Opening phase ($t_h^{\mathrm{open}} \le t \le T$) : Open the hand until the position of x_h results in zero with the operating velocity of v_h, as shown in Fig.2(iii).

Fig.4 gives an overview of the experimental system, where a dummy hand with two parallel grippers with the stiffness of k_h is utilized. One gripper is fixed on the base and the other can be moved by a linear slider, so that they can realize smooth opening and closing motions. The base displacement of the gripper $x_h(t)$ is measured by an encoder integrated in the motor for driving the slider. The normal component of contact force at the contact point $f(t)$ is measured by the strain gauge attached to the gripper. By inserting the measured $x_h(t)$ and $f(t)$ into Eq.(12), we can compute A_1, A_2, B_1, and B_2. In order to avoid a large error induced by differentiating the noisy signal, instead of using Eq.(12), we transform Eq.(12) to the following integration equation:

$$\boldsymbol{M}\boldsymbol{p} = \boldsymbol{q}, \quad (17)$$

where

$$\boldsymbol{M} \triangleq \left[-\boldsymbol{f}, \ -\int \boldsymbol{f} dt, \ \boldsymbol{x}_h, \ \int \boldsymbol{x}_h dt \right], \quad (18)$$

$$\boldsymbol{p} \triangleq [A_2, A_1, B_2, B_1]^T, \quad (19)$$

$$\boldsymbol{q} \triangleq \iint \boldsymbol{f} dt^2, \quad (20)$$

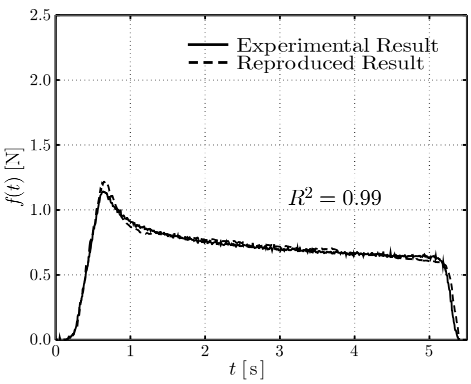
$$\boldsymbol{f} \triangleq [f(t_1), f(t_2), \ldots, f(t_n)]^T, \quad (21)$$

$$\boldsymbol{x}_h \triangleq [x_h(t_1), x_h(t_2), \ldots, x_h(t_n)]^T, \quad (22)$$

$f(t_i)$ and $x_h(t_i)$ are the contact force and the base displacement of hand, respectively, at the sampling time t_i ($i = 1, 2, \cdots, n$). From Eq.(17), we can estimate $\boldsymbol{p}$ by the least squares method as follows:

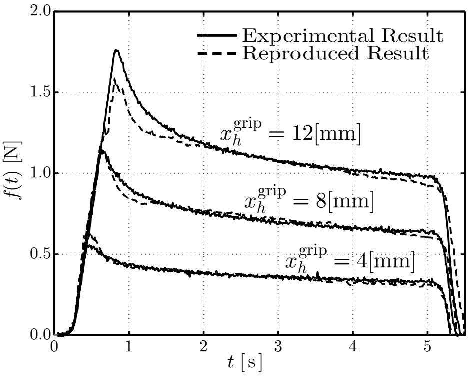
$$\boldsymbol{p} = (\boldsymbol{M}^T \boldsymbol{M})^{-1} \boldsymbol{M}^T \boldsymbol{q}. \quad (23)$$

After computing $\boldsymbol{p}$ by using experimental data, the viscoelastic parameters c_i and k_i can be computed from Eqs.(13)–(16), as



$k_1 = 300$[N/m] $k_2 = 180$[N/m]
$c_1 = 1400$[Ns/m] $c_2 = 63$[Ns/m]

Fig. 5. The output of $f(t)$ with respect to time.



$k_1 = 280$[N/m] $k_2 = 180$[N/m]
$c_1 = 1400$[Ns/m] $c_2 = 62$[Ns/m]

Fig. 6. The output of $f(t)$ with respect to time under various $x_h^{\rm grip}$.

follows:

$$k_1 = \frac{B_2}{A_2}, \tag{24}$$

$$k_2 = \frac{{B_1}^2 B_2}{A_2 {B_1}^2 - A_1 B_1 B_2 + {B_2}^2}, \tag{25}$$

$$c_1 = B_1, \tag{26}$$

$$c_2 = \frac{B_1 {B_2}^2}{A_2 {B_1}^2 - A_1 B_1 B_2 + {B_2}^2}. \tag{27}$$

3.3. Results of Estimation

We adopt a popular Norimaki as an object for the experiment, where the hand stiffness k_h, the operating velocity v_h, the base displacement $x_h^{\rm grip}$, the time for finishing the closing motion is $t_h^{\rm grip}$, and the time for starting the opening motion is $t_h^{\rm open}$ are 8500[N/m], 20[mm/s], 8[mm], 0.8[s], and 5.0[s], respectively. The continuous line in Fig.5 shows the contact force between the hand and the object with respect to time. From this line, we can see that: the contact force increases in the closing phase ($0 \leq t < 0.8$[s]), the contact force relaxes in the stationary phase ($0.8 \leq t < 5.0$[s]), and the contact force rapidly decreases in the opening phase ($5.0 \leq t \leq 5.5$[s]). The viscoelastic parameters c_i and k_i are estimated by using the contact force data in Fig.5, are indicated as well in Fig.5. The dashed line in Fig.5 shows the reproduced contact force computed by using Eqs.(12)–(16) with the estimated parameters k_i, c_i and the hand position data $x_h(t)$, respectively. We can see that the reproduced contact force nicely matches with that obtained by the experiment, where the degree of approximation is given by $R^2 = 0.99$. In order to obtain the average parameters of Norimaki, we execute experiments for three different base displacements $x_h^{\rm grip} = \{4, 8, 12\}$[mm], and performed ten times estimations for each displacement. In Fig.6, we show the average of estimated viscoelastic parameters. The continuous line and the dashed line in Fig.6 show one of the experimental contact force and the reproduced contact force, respectively, for $x_h^{\rm grip} = \{4, 8, 12\}$[mm]. The average of parameters in Fig.6 are utilized for the analysis in Section 4.

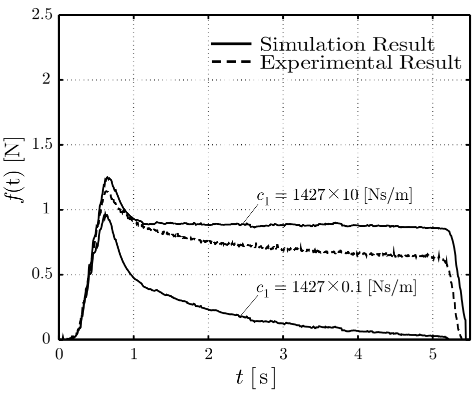


Fig. 7. The simulation results under the change of parameter c_1.

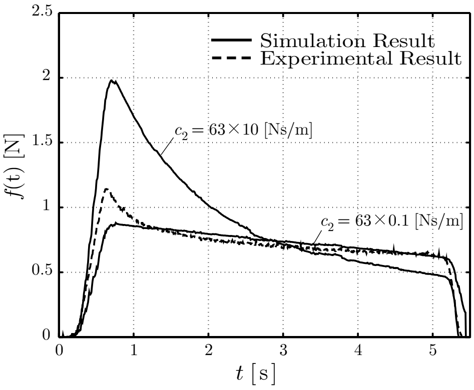


Fig. 8. The simulation results under change of parameter c_2.

3.4. Parameter Sensitivity

Based on the experimental result as shown in Fig.5, where we can see that viscous element c_1 is extremely lager than c_2, let us examine the parameter sensitivity in the Burger model. In order to examine how each viscous parameter effects on the three handling phases, we compute the contact force when the viscous parameters c_1 and c_2 are changed. Fig.7 and Fig.8 show the computed contact forces, where the viscous elements c_1 and c_2 are set by ten times or one over ten of the estimated parameter, respectively. From Fig.7, we can see that under the viscous parameter c_1 with ten times more than the original one, the force relaxation arises in only initial part of the stationary phase, and the constant force is maintained. Under the c_1 with one over ten of the original one, the contact force decreases drastically after the closing phase. Based on these observations, the viscous element c_1 influences on the contact force in the stationary phase, and this parameter concerns with keeping the grasp of the object while the hand lifts up the object. From Fig.8, we can see that the viscous element c_2 is important to generate the contact force in the closing phase, and this parameter is concerned with the initial increase of force during the phase.

4. Simulation and Optimum Design

In this section, we consider the optimum design, where we regard both the hand stiffness k_h and the operating velocity v_h as the design parameters of the hand.

4.1. Definition of Plastic Deformation and Total Working Time

For a given set of the base displacement of the hand in the stationary phase x_h^{grip} and the operating velocity in the closing phase v_h, the time for finishing the closing phase t_h^{grip} is determined as follows:

$$t_h^{\text{grip}} = \left| \frac{x_h^{\text{grip}}}{v_h} \right|. \tag{28}$$

On the other hand, the time for starting the opening phase t_h^{open} has to be determined according to the transporting time T_l. Suppose that the transporting time T_l is given. For avoiding that the hand drops the object, the following condition for normal component of the contact force is required:

$$mg\alpha \leq 2\mu f, \tag{29}$$

where m, g, μ, and α are the mass of object, the gravitational acceleration, the friction coefficient between the hand and the object, and the safety factor[1], respectively. From Eq.(29), we can express the limitation of contact force as follows:

$$f^{\text{lim}} \triangleq \frac{mg\alpha}{2\mu}. \tag{30}$$

Suppose that in the closing and the opening phases, there are unique times at which $f(t) = f^{\text{lim}}$, as shown in Fig.2. Such t_1^{lim} and t_2^{lim} are defined by the following conditions:

$$t_1^{\text{lim}} \triangleq t|_{f=f^{\text{lim}}} \quad (0 \leq t_1^{\text{lim}} \leq t_h^{\text{grip}}), \tag{31}$$

$$t_2^{\text{lim}} \triangleq t|_{f=f^{\text{lim}}} \quad (t_h^{\text{open}} \leq t_2^{\text{lim}} \leq T). \tag{32}$$

[1] $\alpha \geq 1$ indicates how much larger the friction force is required to be than the gravity force applied to the object. However, an excessively large α leads to a large contact force, and as a result, to a large plastic deformation.

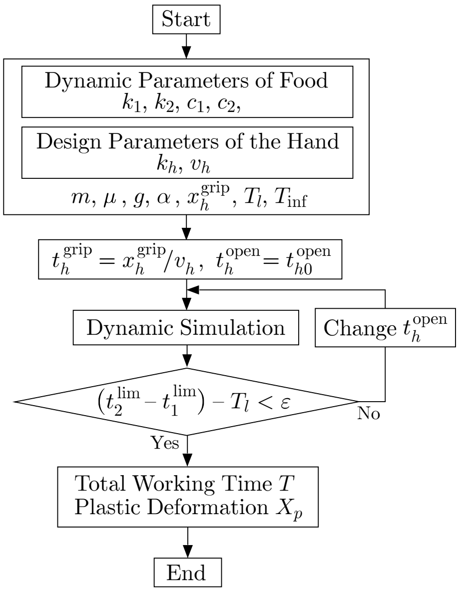


Fig. 9. Flowchart for computing T and X_p.

To guarantee that the hand can support the object for the time T_l of the transport of object, the following condition is further required:

$$t_2^{\text{lim}} - t_1^{\text{lim}} \geq T_l. \tag{33}$$

To minimize the total working time T, let us consider the time for starting the opening phase t_h^{open} so that it leads to

$$t_2^{\text{lim}} - t_1^{\text{lim}} = T_l. \tag{34}$$

Under the above t_h^{grip} and t_h^{open}, we define the total working time T and the plastic deformation X_p as follows:

$$T \triangleq t_h^{\text{open}} + \left| \frac{x_h^{\text{grip}}}{v_h^{\max}} \right|, \tag{35}$$

$$X_p \triangleq x(\infty), \tag{36}$$

where the hand opens with the maximum velocity $v_h^{\max}$ in the opening phase, for simplicity.

4.2. Simulation and Optimum Design

We perform simulation based on the viscoelastic parameters obtained by the experiments. For the hand motion in each phase, the behavior of the object $x(t)$ can be computed by simulation based on Eqs.(11) and (12). Fig.9 shows the flowchart for computing T and X_p. Instead of using Eq.(36), the plastic deformation is computed by $X_p = x(T + T_{\text{inf}})$, where T_{inf} is given large enough to ensure that the object completes the recovering motion after being released. Table I shows the parameters used for the simulation. Fig.10 shows the simulation result of the total working time T and the plastic deformation X_p under the variable parameters of the hand stiffness $k_h^{\min} \leq k_h \leq k_h^{\max}$ and the operating velocity $v_h^{\min} \leq v_h \leq v_h^{\max}$. We would note that this simulation result described by a curved surface is equivalent to that obtained

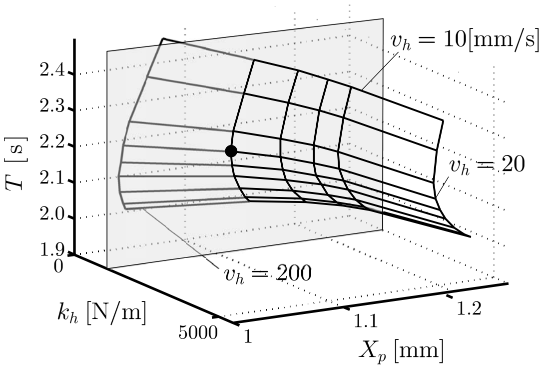


Fig. 10. The optimum design point.

by the Maxwell model [1]. Based on the simulation result, we can solve the optimum design problem to minimize the plastic deformation X_p as follows:

$$\begin{aligned}
&\text{Minimize} && X_p\\
&\text{Subject to} && f^{\lim} \le f(t),\ \ t_1^{\lim} \le t \le t_2^{\lim},\\
& && t_2^{\lim} - t_1^{\lim} \ge T_l,\\
& && T \le T^{\max},\\
& && k_h^{\lim} \le k_h,\\
& && v_h^{\min} \le v_h \le v_h^{\max},\\
& && k_h^{\min} \le k_h \le k_h^{\max},
\end{aligned}$$

where $k_h^{\lim}$, $T^{\max}$, and $X_p^{\max}$ are the minimum hand stiffness, the permissible total working time, and the permissible plastic deformation, respectively. We compute the optimum operating velocity v_h^* and the optimum stiffness k_h^* to minimize the plastic deformation X_p of food. When $k_h^{\lim} = 1000$[N/m], $T^{\max} = 2.20$[s], and $X_p^{\max} = 1.2$[mm] are given, the minimum plastic deformation X_p obtained from Fig.10 is $X_p = 1.12$[mm] (Point • indicated in Fig.10). In this case, v_h^*, k_h^*, and T are also obtained and given by $v_h^* = 20$[mm/s], $k_h^* = 1000$[N/m], and $T = 2.17$[s], respectively.

5. Discussion

Now, let us focus on just the resultant plastic deformation X_p. For the Burger model, the plastic deformation X_p depends only upon the deformation of $x_3(t)$ for c_1 during the contact between the object and the hand, since the deformations of x_1 and x_2 are completely recovered by the elastic elements of k_1 and k_2 at the infinite time, respectively, as shown in Fig.3. Therefore, from Eqs.(1) and (5), we can obtain X_p as follows:

$$X_p = x_3(T), \tag{37}$$

$$= \frac{1}{c_1}\int_0^T f(t)dt. \tag{38}$$

From Eq.(38), we can obtain X_p by computing for only the total working time of hand T, instead of an infinite time as shown in Eq.(36). This is a great advantage from the viewpoint of the exact computation of X_p.

TABLE I
PARAMETERS FOR SIMULATION.

k_1	single elastic parameter	280 [N/m]
k_2	elastic parameter in the parallel unit	180 [N/m]
c_1	single viscous parameter	1400 [Ns/m]
c_2	viscous parameter in the parallel unit	62 [Ns/m]
T_l	time for lifting object	2.0 [s]
m	mass of object	0.045 [kg]
μ	coefficient of friction	1.2
g	acceleration due to gravity	9.8 [m/s^2]
$x_h^{\rm grip}$	root displacement of hand	8.0 [mm]
$v_h^{\min}$	minimum speed of the hand	10 [mm/s]
$v_h^{\max}$	maximum speed of the hand	200 [mm/s]
$k_h^{\min}$	minimum stiffness of hand	500 [N/m]
$k_h^{\max}$	maximum stiffness of hand	5000 [N/m]
α	safety factor	3
$T_{\rm inf}$	additional time for restoration of food	3.0 [s]

6. Conclusion

We discussed a design approach on robotic food handling by considering the characteristics of viscoelasticity. The main results in this paper are summarized as follows:

1) Based on the Burger model, we experimentally obtained the viscoelastic parameters of Norimaki.
2) We showed an example of the optimum design, where we determined the optimum combination of the hand stiffness and the operating velocity of the hand to minimize the plastic deformation.
3) We showed that the Burger model has an advantage from the viewpoint of the exact plastic deformation of object.

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