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ORIGINAL RESEARCH PAPER

# An optimum design of robotic food handling by using Burger model

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**Abstract** This paper discusses an optimum design approach on robotic food handling by considering the characteristics of viscoelasticity of object. We pick up a traditional Japanese food, "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 · Optimum design

## 1 Introduction

At present, dishing up foods into a box lunch sold at convenience stores is done manually by workers standing on both sides of a belt conveyor, as shown in Fig. 1. 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. 2. 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. 3(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. 3(ii), and the opening phase where the hand base position opens for releasing the object, as shown in Fig. 3(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 and for continuously imparting a grasping force to food under the change of its shape with respect to time. Taking the above requirements and the characteristics of object into account,

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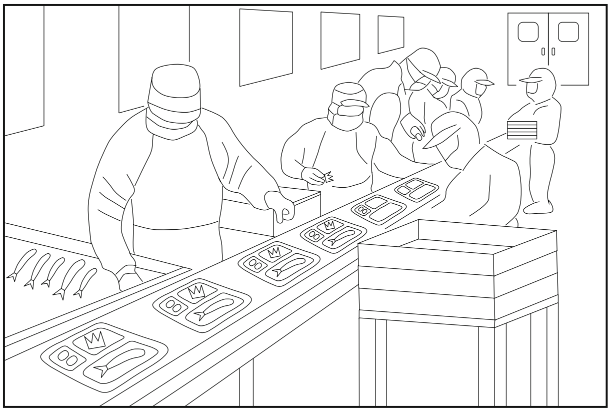
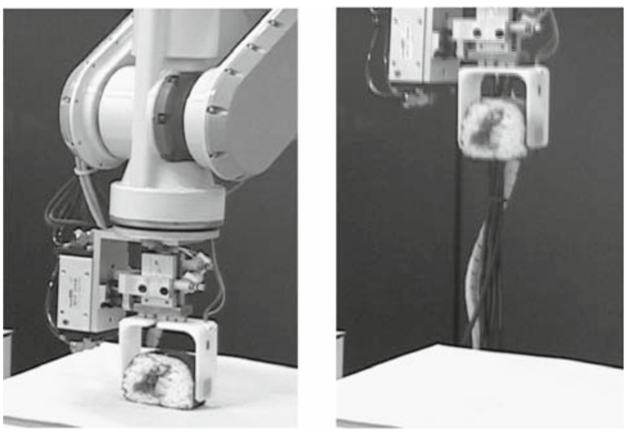


**Fig. 1** An overview of production factory of box lunches



**(a)** Gripping motion **(b)** Lifting motion

**Fig. 2** An example of robotic food handling

this paper discusses a design approach on robotic handling for a viscoelastic object based on the Burger model.

After obtaining the viscoelastic parameters of Norimaki based on the Burger model through experiments, we explore how the parameters affect 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.

This paper is organized as follows: in Sect. 2, we briefly review related works. In Sect. 3, we explain the Burger model and how to estimate the parameters of object. In Sect. 4, we obtain the viscoelastic parameters of Norimaki through experiments, and give discussion on the parameter sensitivity. In Sect. 5, 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 Sect. 6, we discuss how to compute the plastic deformation of object. In Sect. 7, we conclude this paper.

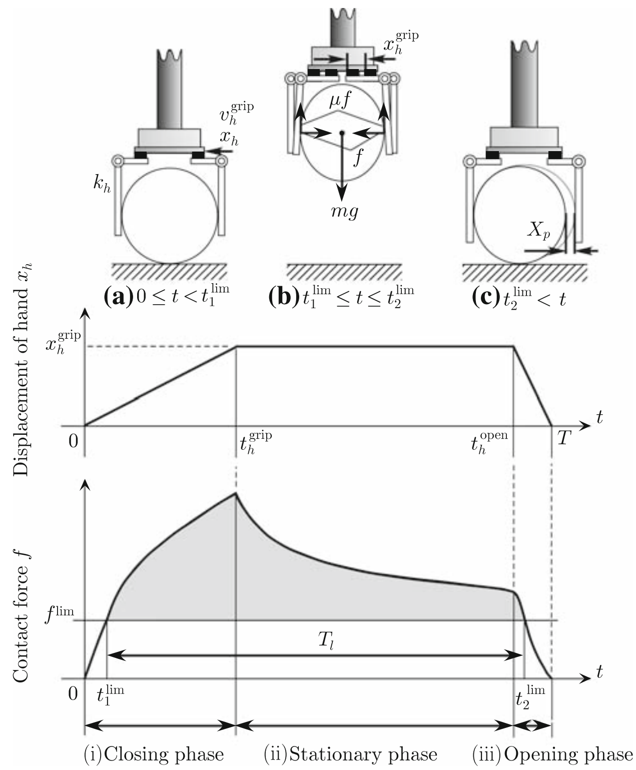



**Fig. 3** Three phases for handling a food

## 2 Related works

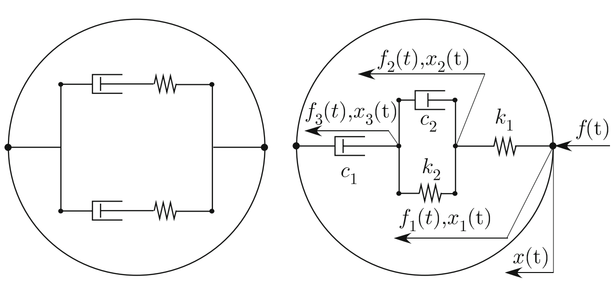
Robotic systems and automations for food processing have been desired by the food industry for a long time. As for deformations of food, Tokumoto et al. [1] have shown that a proper combination of both elastic and viscous elements can express the basic behavior of rheology objects. They have also shown simulation results for confirming the validity of the model. As for food handling robots, Li and Lee [2] have developed a visually guided robotic system for handling food. They have shown that the gripper grasps food robustly by visual information. Silsoe Research Institute [3] has developed the robot hand capable of handling a food with adhesion characteristics. The hand is composed of a pair of gripping finger and a film like a kind of belt conveyor, can release such an object accurately. Sakamoto et al. [4] 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] has 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 apply automatic assembly tasks.

## 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. 4 [9]. While a Maxwell model as shown in Fig. 4a is applied to approximate characteristic of stress relaxation, each serial viscoelastic unit has a different relaxation time constant. Our former work [4] 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. 4a. While the same unit is utilized in parallel, it is often the case where the estimated values of elements 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. 4b. 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 and this part of deformation can be completely recovered. 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. 4b, where $x$, $x_i$, and $f_i$ $(i = 1, 2, 3)$ are the whole deformation of the object, the deformation of ea. 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




**(a)** Maxwell model **(b)** Burger model

**Fig. 4** Two viscoelastic model for approximating a food

the normal component of force. By the relationship between the force and the displacement in each element, we can obtain the following equations:

$$f(t) = f_i(t), \tag{1}$$

$$x(t) = x_1(t), \tag{2}$$

$$f_1(t) = k_1(x_1(t) - x_2(t)), \tag{3}$$

$$f_2(t) = k_2(x_2(t) - x_3(t)) + c_2(\dot{x}_2(t) - \dot{x}_3(t)), \tag{4}$$

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

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

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

where

$$b_2 \triangleq \frac{c_1c_2}{k_2}, \tag{7}$$

$$b_1 \triangleq c_1, \tag{8}$$

$$a_2 \triangleq \frac{c_1c_2}{k_1k_2}, \tag{9}$$

$$a_1 \triangleq \frac{c_1k_1 + c_1k_2 + c_2k_1}{k_1k_2}. \tag{10}$$

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. 3. By letting $x_h$ be the displacement of the base of hand, we obtain

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

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

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

where

$$B_2 \triangleq \frac{c_1c_2}{k_2}, \tag{13}$$

$$B_1 \triangleq c_1, \tag{14}$$

$$A_2 \triangleq \frac{c_1c_2(k_1 + k_h)}{k_1k_2k_h}, \tag{15}$$

$$A_1 \triangleq \frac{c_1k_1k_2 + k_h(k_1c_2 + k_1c_1 + k_2c_1)}{k_1k_2k_h}. \tag{16}$$

We would now note that Eq. (12) is equivalent to the equation of motion obtained by utilizing the Maxwell model [4], 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 further suppose that the commands for open and close to the hand are given in the following procedure:

1. *Closing phase* ($0 \le t < t_h^{\mathrm{grip}}$). Close the hand until the position of $x_h$ results in $x_h^{\mathrm{grip}}$ with the operating velocity of $v_h^{\mathrm{grip}} (= \dot{x}_h)$, as shown in Fig. 3(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. 3(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 $v_h^{\mathrm{open}}$, as shown in Fig. 3(iii).

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:

$$M\, p = q, \tag{17}$$

where

$$M \triangleq \begin{bmatrix} -f(t_1), & -\int f(t_1)\mathrm{d}t, & x_h(t_1), & \int x_h(t_1)\mathrm{d}t \\ -f(t_2), & -\int f(t_2)\mathrm{d}t, & x_h(t_2), & \int x_h(t_2)\mathrm{d}t \\ \vdots & \vdots & \vdots & \vdots \\ -f(t_n), & -\int f(t_n)\mathrm{d}t, & x_h(t_n), & \int x_h(t_n)\mathrm{d}t \end{bmatrix} \tag{18}$$

$$p \triangleq [A_2, A_1, B_2, B_1]^T, \tag{19}$$

$$q \triangleq \left[\iint f(t_1)\mathrm{d}t^2, \iint f(t_2)\mathrm{d}t^2, \ldots, \iint f(t_n)\mathrm{d}t^2\right] \tag{20}$$

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

$$p = (M^T M)^{-1} M^T q. \tag{21}$$

After computing $p$ by using experimental data, the viscoelastic parameters $c_i$ and $k_i$ ($i = 1, 2$) can be computed from Eqs. (13)–(16), as follows:

$$k_1 = \frac{B_2 k_h}{A_2 k_h - B_2}, \tag{22}$$

$$k_2 = \frac{{B_1}^2 B_2}{A_1 B_1 B_2 - A_2 {B_1}^2 - {B_2}^2}, \tag{23}$$

$$c_1 = B_1, \tag{24}$$

$$c_2 = \frac{B_1 {B_2}^2}{A_1 B_1 B_2 - A_2 {B_1}^2 - {B_2}^2}. \tag{25}$$

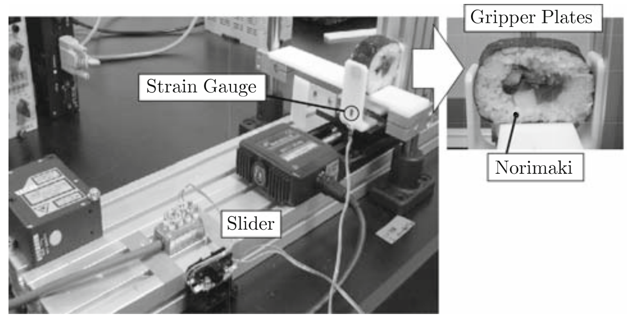



**Fig. 5** Experimental system

We would note that $k_1$ results in $B_2/A_2$ when $k_h$ is large enough.

## 4 Experiments

### 4.1 Experimental system

Figure 5 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 the encoder integrated in the motor for driving the slider. The normal component of contact force $f(t)$ is measured by the strain gauge attached to the gripper.

### 4.2 Experimental result

We adopt a popular Norimaki as an object for the experiment, where the hand stiffness $k_h$, the operating velocity in closing phase $v_h^{\mathrm{grip}}$, the operating velocity in opening phase $v_h^{\mathrm{open}}$, the base displacement $x_h^{\mathrm{grip}}$, the time for finishing the closing motion is $t_h^{\mathrm{grip}}$, and the time for starting the opening motion is $t_h^{\mathrm{open}}$ are 8500 N/m, 20 mm/s, 20 mm/s, 8 mm, 0.8 s, and 5.0 s, respectively. The continuous line in Fig. 6 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 ($0 \le t < 0.8$ s), the contact force relaxes in the stationary phase ($0.8 \le t < 5.0$ [s]), and the contact force rapidly decreases in the opening phase ($5.0 \le t \le 5.5$ s), respectively.

#### 4.2.1 Parameter estimation

The viscoelastic parameters $c_i$ and $k_i$ are estimated by using the contact force data in Fig. 6, are indicated as well in Fig. 6, where the dashed line in Fig. 6 shows the reproduced contact force computed by using Eqs. (12)–(16) with

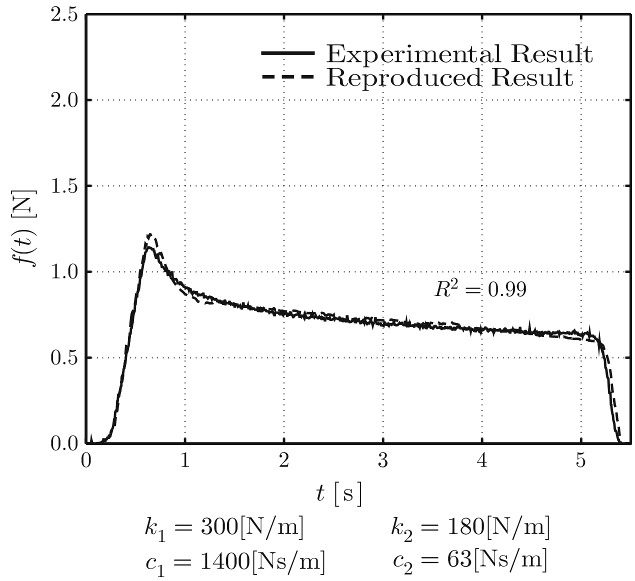



**Fig. 6** The output of $f(t)$ with respect to time

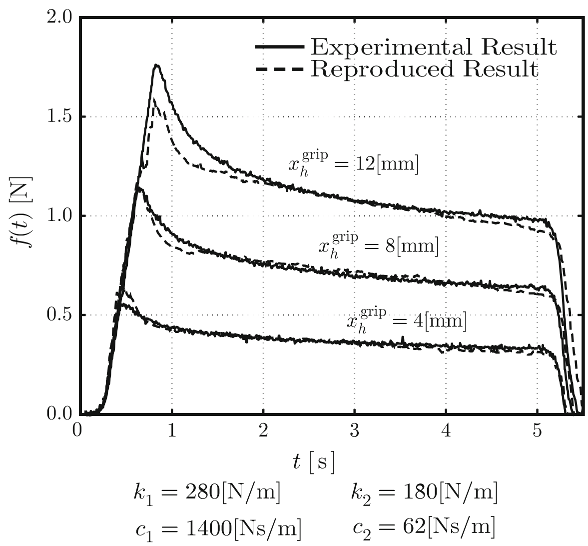



**Fig. 7** The output of $f(t)$ with respect to time under various $x_h^{grip}$

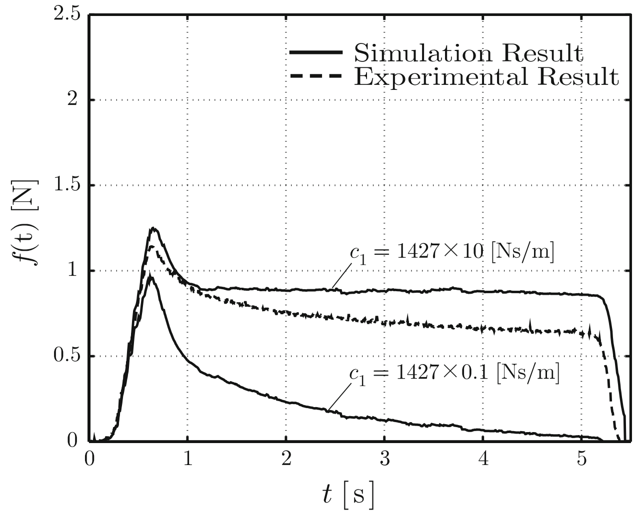



**Fig. 8** The simulation results under the change of parameter $c_1$

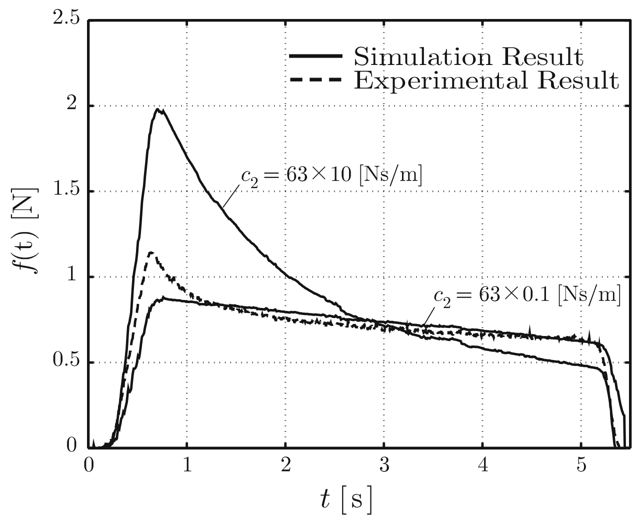



**Fig. 9** The simulation results under change of parameter $c_2$

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 $x_h^{grip} = \{4, 8, 12\}$ mm, and performed ten times estimations for each displacement. In Fig. 7, we show the average of estimated viscoelastic parameters. The continuous line and the dashed line in Fig. 7 show one of the experimental contact force and the reproduced contact force, respectively, for $x_h^{grip} = \{4, 8, 12\}$ mm. The average of parameters in Fig. 7 are utilized for the analysis in Sect. 5.

*4.2.2 Parameter sensitivity*

From Fig. 6, we can see that the viscous element $c_1$ is extremely lager than $c_2$. Let us now examine the parameter sensitivity in the Burger model. In order to examine how each viscous parameter affect on the three handling phases, we compute the contact force when the viscous parameters $c_1$ and $c_2$ are changed. Figures 8 and 9 show the computed contact forces, where the viscous elements $c_1$ and $c_2$ are set by ten or one over ten times of the estimated parameter, respectively. From Fig. 8, 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 force is then keeps nearly constant till the opening motion. 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 $c_1$

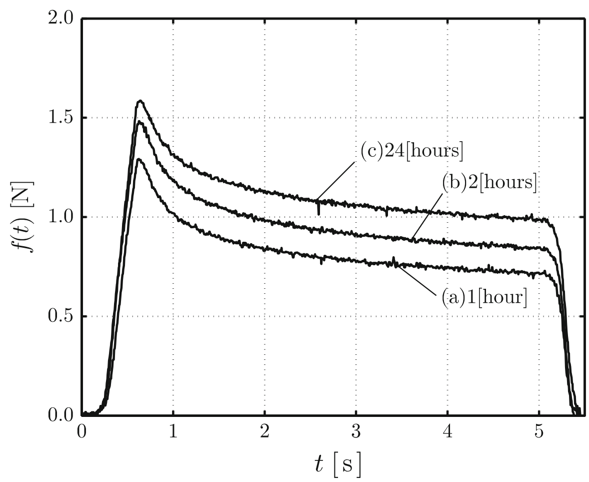



**Fig. 10** The effect of time after the objects are produced

mainly controls 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. 9, 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. Figure 10 shows how the contact force is affected by the time after the objects are produced, where (a), (b) and (c) show results by using objects one, two and twenty four hours after they are produced, respectively. From Fig. 10, we can see that the contact force generally increase as the time after production increases, while the additional increase under twenty four hours after production is only 20% of that under two hours after production. From Fig. 10, we neglect the time dependency of parameters of Norimaki after two hours have passed. From these discussions, while dynamic parameters change depending upon foods. Once foods are fixed in the lunch box factory, their dynamic parameters change little for a flow of same foods. Therefore, the parameter estimation itself is not so sensitive to the solution of the optimum problem we are handling in the next chapter.

## 5 Optimum design

In this section, we consider the optimum design, where we regard both the hand stiffness $k_h$ and the operating velocity $v_h^{\text{grip}}$ and $v_h^{\text{open}}$ as the design parameters of the hand.

### 5.1 Definition of plastic deformation and total working time

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

$$t_h^{\text{grip}} = \left| \frac{x_h^{\text{grip}}}{v_h^{\text{grip}}} \right|. \tag{26}$$

On the other hand, the time for starting the opening phase $t_h^{\text{open}}$ 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:

$$mg\alpha \leq 2\mu f, \tag{27}$$

where $m$, $g$, $\mu$, and $\alpha$ 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. (27), we can express the limitation of contact force as follows:

$$f^{\text{lim}} \triangleq \frac{mg\alpha}{2\mu}. \tag{28}$$

Suppose that in the closing and the opening phases, there are unique times at which $f(t) = f^{\text{lim}}$, as shown in Fig. 3. Such $t_1^{\text{lim}}$ and $t_2^{\text{lim}}$ are defined by the following conditions:

$$t_1^{\text{lim}} \triangleq t|_{f=f^{\text{lim}}} \quad (0 \leq t_1^{\text{lim}} \leq t_h^{\text{grip}}), \tag{29}$$

$$t_2^{\text{lim}} \triangleq t|_{f=f^{\text{lim}}} \quad (t_h^{\text{open}} \leq t_2^{\text{lim}} \leq T). \tag{30}$$

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:

$$t_2^{\text{lim}} - t_1^{\text{lim}} \geq T_l, \tag{31}$$

$t_h^{\text{open}}$ is determined in the following. First, we assume the initial time for starting the opening phase $t_{h0}^{\text{open}} = t_1^{\text{lim}} + T_l$. Then, we solve the dynamic behavior of the object by using the simulation tool (MSC. ADAMS). Since the solution includes the force pattern $f(t)$ with respect to time $t$, we can obtain $t_1^{\text{lim}}$ and $t_2^{\text{lim}}$. However, the computed $t_1^{\text{lim}}$ and $t_2^{\text{lim}}$ are not satisfied with the relationship $t_2^{\text{lim}} - t_1^{\text{lim}} = T_l$ in general. In the next step, we change $t_h^{\text{open}}$ to $t_h^{\text{open}} - \Delta t$ until $|t_2^{\text{lim}} - t_1^{\text{lim}} - T_l| < \varepsilon$ where $\varepsilon$ is a small positive value. This process is given in Fig. 11 showing the flowchart. Under the above $t_h^{\text{grip}}$ and $t_h^{\text{open}}$, we define the total working time $T$ and the plastic deformation $X_p$ as follows:

$$T \triangleq t_h^{\text{open}} + \left| \frac{x_h^{\text{grip}}}{v_h^{\max}} \right|, \tag{32}$$

$$X_p \triangleq x(\infty), \tag{33}$$

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

[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 $\alpha$ leads to a large contact force, and as a result, to a large plastic deformation.

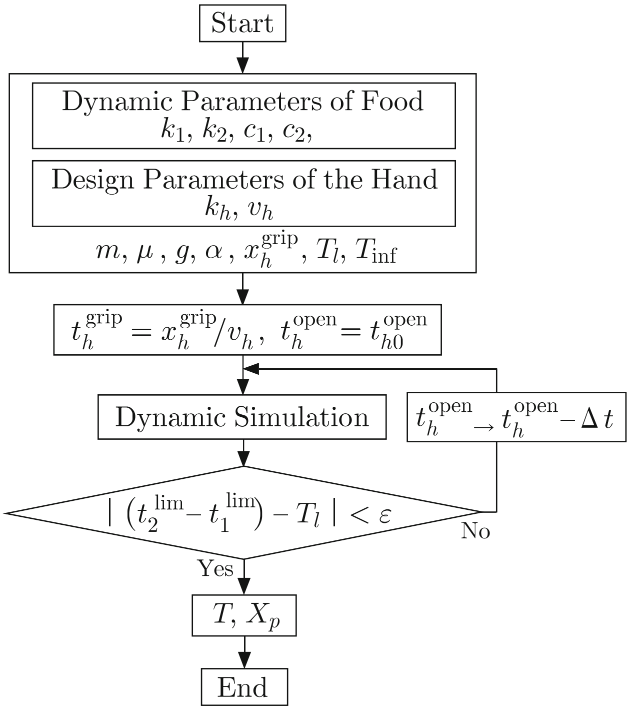



**Fig. 11** Flowchart for computing $T$ and $X_p$

5.2 Optimum design for minimum plastic deformation

We perform simulation based on the viscoelastic parameters obtained by the experiments. Figure 11 shows the flowchart for computing $T$ and $X_p$. For the hand motion in each phase, $x(t)$ can be computed by Eqs. (11) and (12). Instead of using Eq. (33), the plastic deformation is computed by $X_p = x(T + T_{inf})$, where $T_{inf}$ is given large enough to ensure that the object completes the recovering motion after released. Table 1 shows the parameters used for the simulation. Figure 12 shows the simulation result of the total working time $T$ and the plastic deformation $X_p$ under the variable parameters of the hand stiffness $k_h^{min} \le k_h \le k_h^{max}$ and the operating velocity $v_h^{min} \le v_h^{grip} \le v_h^{max}$. Based on the simulation result, we can solve the optimum design problem to minimize the plastic deformation $X_p$ as follows:

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

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. By utilizing the exhaustive

**Table 1** Parameters for simulation

| | | |
|---|---|---|
| $k_1$ | Single elastic parameter (N/m) | 280 |
| $k_2$ | Elastic parameter in the parallel unit (N/m) | 180 |
| $c_1$ | Single viscous parameter (N s/m) | 1400 |
| $c_2$ | Viscous parameter in the parallel unit (N s/m) | 62 |
| $T_l$ | Time for lifting object (s) | 2.0 |
| $m$ | Mass of object (kg) | 0.045 |
| $\mu$ | Coefficient of friction | 1.2 |
| $g$ | Acceleration due to gravity (m/s$^2$) | 9.8 |
| $x_h^{grip}$ | Root displacement of hand (mm) | 8.0 |
| $v_h^{min}$ | Minimum speed of the hand (mm/s) | 10 |
| $v_h^{max}$ | Maximum speed of the hand (mm/s) | 200 |
| $k_h^{min}$ | Minimum stiffness of hand (N/m) | 500 |
| $k_h^{max}$ | Maximum stiffness of hand (N/m) | 5000 |
| $\alpha$ | Safety factor | 3 |
| $T_{inf}$ | Additional time for restoration of food (s) | 3.0 |

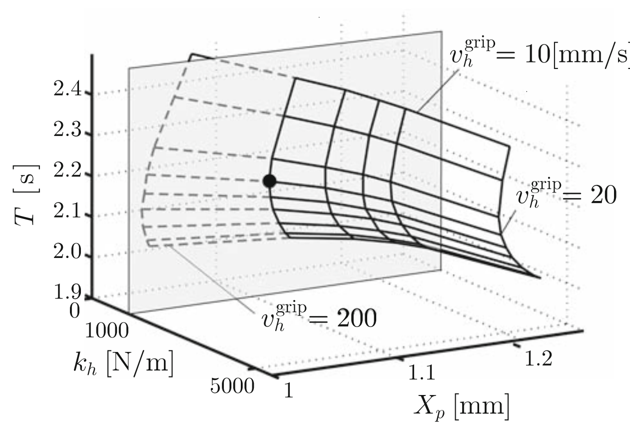



**Fig. 12** Simulation result

search method, we can compute the optimum operating velocity $v_h^{*grip}$ 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. 12 is $X_p = 1.12$ mm (Point • indicated in Fig. 12). In this case, $v_h^{*grip}$, $k_h^*$, and $T$ are also obtained and given by $v_h^{*grip} = 20$ mm/s, $k_h^* = 1000$ N/m, and $T = 2.17$ s, respectively. From the simulation result, we can see that the optimum hand stiffness is obtained on the minimum boundary, while the optimum velocity is not on the boundary. From the geometrical shape of the graph in Fig. 12, the optimum point can be found on the plane corresponding to the minimum boundary of specified by $k_h = k_h^{min}$. This means that the compliant gripper can contribute to avoid decreasing the contact force for the change of shape of object due to the plastic deformation. On the other hand, it should be noted that the maximum velocity $v_h^{max}$ does not always provide us with

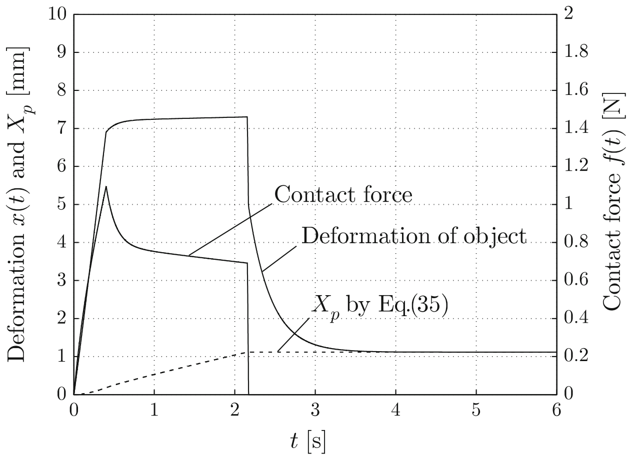



**Fig. 13** Computed result $X_p$ by Eq. (35)

the optimum velocity for reducing the plastic deformation, while it provides us with the minimum operation time $T$.

## 6 Discussion

Now, let us focus on 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. 4. Therefore, from Eqs. (1) and (5), we can obtain $X_p$ as follows:

$$X_p = x_3(T), \tag{34}$$

$$= \frac{1}{c_1} \int_0^T f(t)\mathrm{d}t. \tag{35}$$

From Eq. (35), we can obtain $X_p$ by computing for only the total working time of hand $T$, instead of the infinite time as shown in Eq. (33). Figure 13 shows a simulation result to confirm Eq. (35), where viscoelastic parameters are given by $c_1 = 1400$ N s/m, $c_2 = 62$ N s/m, $k_1 = 280$ N/m, and $k_2 = 180$ N/m, respectively, and the hand displacement is set to 8 mm, and hand design parameters are given by the optimum hand stiffness $k_h^* = 1000$ N/m, the optimum operating velocity in closing phase $v_h^{*\mathrm{grip}} = 20$ mm/s, and the operating velocity in opening phase $v_h^{\max} = 200$ mm/s, respectively. From Fig. 13, we can see that the deformation of object converges to $X_p$ computed by Eq. (35). While we do not discuss the robustness in this paper explicitly, we can change the robustness of grasping by simply changing the safety factor $\alpha$ , since it directly controls the grasping force.

## 7 Conclusion

We discussed an optimum design approach on food handling robot hand by considering the characteristics of viscoelasticity of object. 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 optimum design, where we determined the optimum combination of the hand stiffness and the operating velocity of the hand to minimize the plastic deformation.

We believe that this work contributes to provide a guide line for designing food handling robots.

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