Vibration Analysis of Food Material for Non-contact Viscoelasticity Measurement

Takahiro Matsuno, Shinichi Hirai, and Zhongkui Wang
Department of Robotics /Ritsumeikan University, Shiga, Japan
Email: {ma-tsuno@fc, hirai@se, wangzk@fc}.ritsumei.ac.jp

***Abstract*—Viscoelastic properties of food material significantly influence the texture of diet articles. Therefore, there are some methods to measure the viscoelastic properties of food materials. However, extant methods require contact with or breakage of a food material. In this study, a novel method for measuring the viscoelastic properties of food material by using a forced vibration device is presented. In the measurement method, viscoelastic properties of food material are estimated from the amplification ratio and phase difference of food material when forced vibration is applied. The method does not require contact with a food material.**

***Index Terms*—Measurement of food property, Viscoelastic properties of food, Forced vibration device**

I. Introduction

Viscoelasticity of food material is related to the texture of a diet article [1], [2]. In order to realize an apposite texture of food, it is necessary to measure the viscoelasticity of the food material during cooking or after cooking [3]. In the case of the subjective assessment of food material viscoelasticity, an individual samples the food and then estimates the properties. However, there are significant individual differences in subjective assessment, and thus the quantitative measurement of food material viscoelasticity is required [4]. In a previous method the viscoelasticity of food material is measured by a creep test [3], [4] and a measurement method that uses Hertzian contact stress theory [5], [6]. However, these measurement methods require contact with the food. In the case of Hertzian contact stress theory, it is necessary to measure the Poisson's ratio. Therefore, this cannot be used for measurement if the Poisson's ratio of food is unknown [5], [6].

It was reported that the material impressions of object related to elasticity were systematically flipped by the phase difference of vibration in visual motion [7], [8]. Patissiers use a technique involving vibration application to a food material and observing the response to measure food properties [9]-[11]. In this method, any object does not need to contact to food material. However, this method corresponds to subjective assessment because the vibration is applied by human hands, and the patissier intuitively understands food properties [9]-[11].

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The present study involves presenting a quantitative measurement method for viscoelastic properties of food material by using a forced vibration device. In the measurement method, the food material is approximated as a simplified model that consists of a linear spring and a damper. The spring coefficient and viscosity coefficient of model are estimated from the amplification ratio and the phase difference of food material when the forced vibration is applied. Subsequently, the Young's modulus of the food material is calculated from the spring coefficient of the simplified model. This method does not require contact with the food material. The prototype forced vibration device and observation system of amplification ratio and phase difference is developed, and the presented measurement method is verified by performing an experiment.

II. Measurement Method Using Forced Vibration

A. Modeling of Food Material

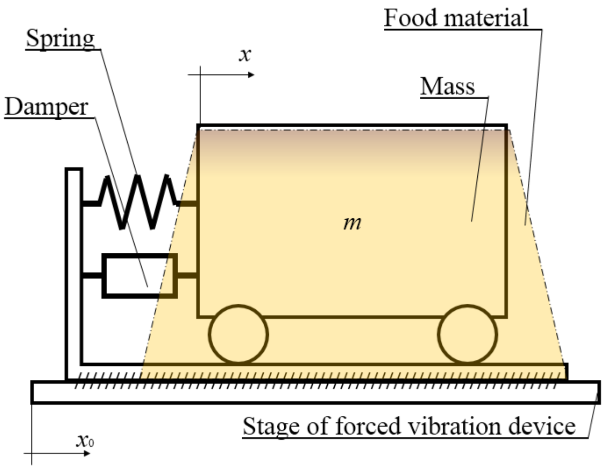

Figure 1. Approximated viscoelastic model of the food material.

In this subsection, the method for calculating the spring constant and viscosity coefficient of the approximate model is presented. The phase difference and amplification ratio of food material vibration are observed when an arbitrary forced vibration is applied. The spring constant and the viscosity coefficient are calculated from the observed phase difference and amplification ratio. First, the food material is approximated as a simplified model that consists of a

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linear spring and a damper as shown in Fig. 1. From the simplified model, equation of motion is given as follows:

$$m\ddot{x} + c(\dot{x} - \dot{x_0}) + k(x - x_0) = 0 \quad (1)$$

where, m, x, x_0, c, and k denote the mass of the food material, horizontal distance of the food material, stage horizontal distance of the forced vibration device, viscosity coefficient, and spring constant, respectively.

In the measurement, the forced vibration is applied to the food material from the stage of the forced vibration device. Therefore, stage horizontal distance x_0 vibrates as follows:

$$x_0 = X_0 \sin \omega t \quad (2)$$

where, X_0, ω, and t denote the amplitude of stage vibration, angular frequency of stage vibration, and time, respectively. If the vibrating material possesses viscosity, the phase difference occurs. The phase difference of the food material vibration is calculated as follows [12], [13]:

$$\theta = \tan^{-1} \frac{c\omega}{-m\omega^2 + k} \quad (3)$$

where θ denotes the phase difference. The amplification ratio of the food material for the input forced vibration is obtained from [12], [13] as follows:

$$T = \frac{X}{X_0} = \frac{\sqrt{c^2\omega^2 + k^2}}{\sqrt{(-m\omega^2 + k)^2 + c^2\omega^2}} \quad (4)$$

where, T and X denote the amplification ratio of the food material and the amplitude of food material vibration, respectively. Subsequently, the measurement process of the spring constant and the viscosity coefficient are discussed. It is assumed that the phase difference θ and the amplification ratio T are observed for any forced vibration. In this case, the spring constant k and the viscosity coefficient c that satisfies the observed phase difference θ and response magnification T are obtained as follows:

$$k = \frac{\omega}{-1+T^2} \Big(\frac{1}{2} m\omega(-1 + 2T^2 + \cos 2\theta) - \cos^2\theta \frac{1}{\tan\theta} \sqrt{m^2\omega^2(-1 + T^2 \frac{1}{\sin^2\theta})\tan^4\theta} \Big) \quad (5)$$

$$c = \frac{\cos^2\theta}{-1+T^2} \Big(m\omega \tan\theta - \sqrt{m^2\omega^2\tan^2\theta(T^2 - \tan^2\theta + T^2\tan^2\theta)} \Big) \quad (6)$$

It is difficult to measure the phase difference when the viscosity of the food material is excessively low. If the measured phase difference is 0, then it is not possible to calculate the spring constant and viscosity coefficient by eqs. (5) – (6). In this case, the viscosity coefficient is assumed as 0, and the spring constant is calculated as follows:

$$k = \frac{m\omega^2 T}{-1 + T} \quad (7)$$

B. *Calculation of Young's Modulus by Using the Spring Constant of the Model*

The Young's modulus of the food material is calculated from the spring constant of the simplified model obtained in the previous subsection. First, the food material is assumed as an elastic body, and the elastic energy of food material is calculated as follows [14]:

$$U = \int_0^L \frac{(P(L - x_L))^2}{2EI} \mathrm{d}x_L \quad (8)$$

where, U, P, L, x_L, E, and I denote the elastic energy of food material, applied load to food material, total height of the food material, optional height, Young's modulus of the food material, and the shear direction's second moment of area at the optional height, respectively. This study is a fundamental investigation on viscoelasticity measurement by a forced vibration device, and thus the shape of food material is limited to a frustum. Therefore, the diameter of food material and the shear direction's second moment of area at the optional height are calculated as follows [15], [16]:

$$d = ax_L + d_0 \quad (9)$$

$$I = \frac{\pi d^4}{64} \quad (10)$$

where, d, d_0, and a denote the diameter of food material at the optional height, the diameter at the bottom surface of the food material, and the rate of the diameter change, respectively. The diameter at the bottom surface of the food material d_0 is directly measured from the real food material, and the rate of the diameter change a is calculated from the height and the diameter at the upper surface of the food material. Given these parameters, the elastic energy of food material in which the shape corresponds to a frustum is calculated as follows:

$$U = \int_0^L \frac{64\big(P(L - x_L)\big)^2}{2\pi E(ax_L + d_0)^4} \mathrm{d}x_L = \frac{32L^3P^2}{3\pi d_0^3(d_0 + aL)E} \quad (11)$$

Subsequently, the shear direction deformation is calculated. It is calculated by partially differentiating the elastic energy of the food material in the applied load as follows:

$$\delta = \frac{\partial U}{\partial P} = \frac{64L^3P}{3d_0^3(d_0 + aL)\pi E} \quad (12)$$

When the spring constant is assumed as $k = P/\delta$, the Young's modulus of the food material E is calculated as follows:

$$E = \frac{64L^3k}{3\pi d_0^3(d_0 + aL)} \quad (13)$$

Given these processes, the Young's modulus and the viscosity coefficient of the food material is calculated by using the observed phase difference and amplification ratio.

III. Development of the Device for Measurement

A. Development of the Forced Vibration Device

The concept of the forced vibration device is shown in Fig. 2. The device consists of an eccentric cam, cam follower, motor, and stage. The eccentric cam is connected to the driving shaft of a motor. The diameter of the eccentric cam and width of the cam follower are equal, and therefore this combination is a positive motion cam. The cam follower is connected to the stage. When the motor is derived in a constant rotation speed, the stage corresponds to a vibrated sine wave. In the study, the amplitude of stage vibration is designed as 5 mm.

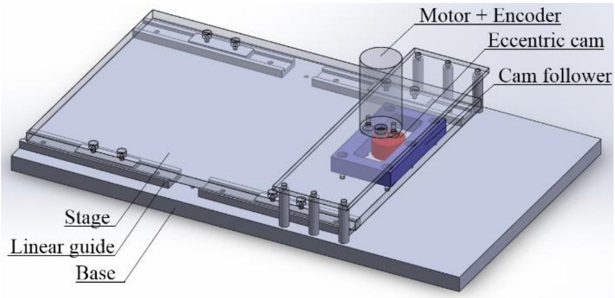

Figure 2. Concept of forced vibration device.

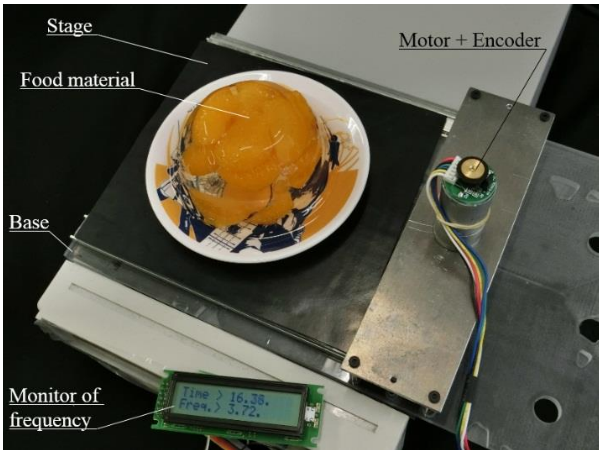

Figure 3. Prototyped forced vibration device.

The prototype forced vibration device is shown in Fig. 3. There is a rubber sheet on the stage of device, and it offers protection from dish slippage when the stage is vibrated at a high frequency. The motor is connected to a stabilized power supply that changes the voltage, and it changes the frequency of stage vibration by adjusting the voltage. Additionally, the motor has an encoder, and the frequency of stage vibration is measured and displayed on the monitor.

B. Measurement Method of the Phase Difference and Response Magnification Factor

In order to measure the phase difference and amplification ratio, the vibrating food material is filmed by using a high-speed camera. This is followed by tracking the characteristic point of the filmed movie, and phase difference and amplification ratio are calculated from the results. In the study, movie analysis software (Kinovea, Joan Charmant & Contrib, France) is used for characteristic point tracking. An example of characteristic point tracking is shown in Fig. 4. With respect to the tracking, any point of the top surface of food material is defined as a characteristic point that represents the position of food. In order to measure the phase difference of food material vibration, the stage vibration is measured by movie analysis. The tracking point is set as a part of the plate or stage. In the analysis software, distance in all directions is measured, and only the horizontal direction distance is selected.

The result of the tracking data represents the distance in the movie, and thus it is necessary to convert the tracking data to a real distance. When the frequency of applied force vibration is sufficiently low, the amplification ratio of food vibration is close to 1. The amplitude of the forced vibration device is 5 mm. Therefore, the amplitude of the food material vibration is close to 5 mm when the frequency of the applied force vibration is sufficiently low. Given these data, the ration of distance of tracking data and real distance is calculated, and the tracking data is converted to real length data. The converted distance data is fitted to a sine function as follows:

$$x(t) = A\sin(\omega t - \varphi) \tag{14}$$

$$x'(t) = A'\sin(\omega t - \varphi') \tag{15}$$

where, $x(t)$, $x'(t)$, A, A', φ, and φ' denote the stage horizontal distance at t, horizontal distance of the food material at t, amplitude of stage vibration, amplitude of food material vibration, phase difference of stage vibration, and phase difference of food material vibration, respectively. The phase difference and the amplification ratio are calculated from the fitted sine function in eq. (14) - (15). The phase difference θ and the amplification ratio T are obtained as follows:

$$T = \frac{A'}{A} \tag{16}$$

$$\theta = \varphi' - \varphi \tag{17}$$

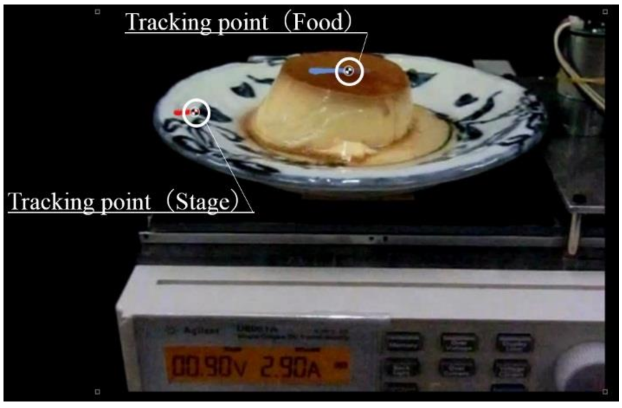

Figure 4. Measurement of phase difference and response magnification factor using image analysis.

Given these processes, the phase difference θ and the amplification ratio T are observed when an optional forced vibration is applied to the food material. The Young's modulus and viscosity coefficient of the food material are calculated by substituting the observed phase difference θ and amplification ratio T in eq. (5) - (7).

IV. Experimental Verification

A. Experiment Setup

In this section, the proposed measurement method that uses a forced vibration device is experimentally verified. First, the food material viscoelasticity is measured by our proposed measurement method. Subsequently, the food material viscoelasticity is measured by a creep test that corresponds to an atypical measurement method, and the measured value is assumed as ground truth. This is followed by discussing the accuracy of our proposed measurement method and comparing it with ground truth.

In the experiment, a commercially available pudding (Morinaga no Yakipurin, Morinaga & Company Ltd., Japan) is used as food material. The shape of the pudding corresponds to a frustum, and the details of the pudding parameters are shown in Table I. The angular frequency of the forced vibration is set between 19.2 rad/s, and forced vibration is applied to the food material by using a prototype forced vibration device. The phase difference θ and the amplification ratio T are measured by a high-speed camera (EXILIM EX - SC200, CASIO, Japan). The Young's modulus and the viscosity coefficient of the food material are calculated with each observed phase difference θ and amplification ratio T.

TABLE I. Type Sizes for Camera-Ready Papers

Mass m	Top diameter	Under diameter
144 g	60 mm	70 mm

B. Experiment Result

The measurement result of the food material vibration by using forced vibration is shown in Fig. 5. The angular frequency of forced vibration is 19.2 rad/s. The phase difference θ and the amplification ratio T are -0.5 rad and 2.5, respectively. Therefore, the values of Young’s modulus and the viscosity coefficient of the food material are 1749 Pa and -0.84 N･s/mm, respectively.

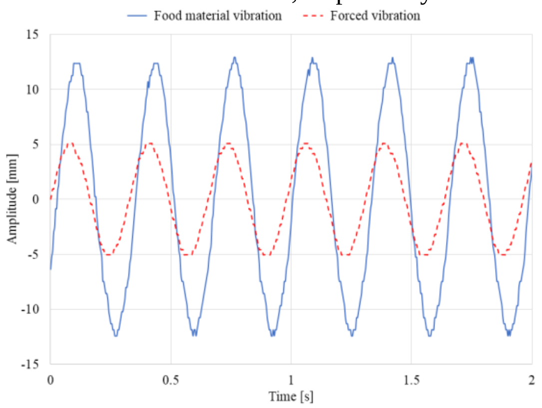

Figure 5. Measurement result of food material vibration.

V. Conclusion

In this study, the method for measuring viscoelasticity of food material by using a forced vibration device was presented. In the method, the food material is approximated as a simplified model that consists of a linear spring and a damper. The spring constant and the viscosity coefficient are calculated from the observed phase difference and amplification ratio. Subsequently, the spring constant of the simplified model is converted to the Young's modulus of the food material. The force vibration device was developed to apply sinusoidal vibration to the food material. The food vibration is recorded by using a high-speed camera, and the phase difference and amplification ratio are measured by movie analysis. The proposed measurement method that uses a forced vibration device was experimentally verified. The experimental results indicated that the method for measuring viscoelasticity of food material involving the use of a forced vibration device successfully measured the Young's modulus and viscosity coefficient of the food material.

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Takahiro Matsuno was born in Japan on July 21, 1989. He received his Ph.D. degree in doctor of engineering from the Ritsumeikan university in 2017.His areas of interest and research are focused on soft robotics, adhesion device, and spring mechanism.

He has been a postdoctoral fellow of global innovation research organization in Ritsumeikan university since 2017. He is author of 2 research papers and 6 proceedings of international conference. He has authored 10 proceedings of national conference.

Dr. Matsuno is a member of the Japan Society of Mechanical Engineers, Robotics Society of Japan, and Japan Society of Spring Engineers. Dr. Matsuno received IEEE International Conference on Real-time Computing and Robotics 2016 Best Student Paper Award Finalist, Japan Society of Spring Engineers Conference on Spring and Restitution Effect 2016 Best Poster Award, IEEE International Conference on Real-time Computing and Robotics 2017 Best Conference Paper Finalist.

Shinichi Hirai was born in Japan on March 19, 1963. He received his Ph.D. degree in doctor of engineering from Kyoto University in 1991. His current research interests are modeling and control of deformable objects, real-time computer vision, and soft-fingered manipulation.

He was a Visiting Researcher with the Massachusetts Institute of Technology in 1989 and was an Assistant Professor with Osaka University from 1990 to 1996. He has been a Professor with the Department of Robotics in Ritsumeikan University since 2002. He is author of 5 books, 12 chapters, 88 research papers, and 230 proceedings of international conference. He has authored 409 proceedings of national conference. Selected published books: Mechanics of Localized Slippage in Tactile Sensing, ISBN 978-3-319-04122-3; Mechanics and Control of Soft-fingered Manipulation, ISBN 978-1-84800-980-6; Why Humans Can Manipulate Objects Despite a Time Delay in the Nervous System, ISBN 978-3-319-03016-6.

Prof. Hirai is a member of IEEE Robotics and Automation Society, Robotics Society of Japan, Japan Society of Mechanical Engineers, and Society of Instrument and Control Engineers. Prof. Hirai received the Society of Instrument and Control Engineers Best Paper Award in 1990, the Japan Society of Mechanical Engineers (JSME) Robotics and Mechatronics Div. Achievement Awards in 1996, the finalist of the Automation Best Paper Award at the 2001 IEEE International Conference on Robotics and Automation, the finalist of the Manipulation Best Paper Award at the 2005 and 2006 IEEE International Conference on Robotics and Automation, the finalist of the Vision Best Paper Award at the 2006 IEEE International Conference on Robotics and Automation, and the Robotics Society of Japan (RSJ) Best Paper Award in 2008.

Zhongkui Wang was born in China on January 20, 1978.He received his Ph.D. degree in doctor of engineering from Ritsumeikan University in 2011.His current research interests are finite element modeling and simulation for medical and nursing applications, optimization-based parameter estimation, tactile sensing and perception, medical instrument development for in vivo measurements, and robotics for food engineering.

He was a Research Associate with the Department of Robotics, Ritsumeikan University, from 2011 to 2012, a Postdoctoral Research Fellow in the same department from 2012 to 2014, and an Academic Guest with the Institute of Robotics and Intelligent Systems, Swiss Federal Institutes of Technology, Zurich, Switzerland, from 2012 to 2013. He has been an Assistant Professor with the Department of Robotics, Ritsumeikan University since 2014. He is author of 11 research papers and 33 proceedings of international conference. He has authored 22 proceedings of national conference.

Dr. Wang is a member of Japanese Society for Medical and BioEngineering. Dr. Wang received SIMULIA Community Conference 2015 favorite poster award, IEEE International Conference on Real-time Computing and Robotics 2017 Best Conference Paper Finalist.