euspen's 19th International Conference & Exhibition, Bilbao, ES, June 2019
www.euspen.eu

Measurement of mechanical characteristics using micro devices with force sensing

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Abstract Treating living organisms requires careful work in microscopic surgery and bio-engineering. However, the measurement accuracy of sensors tends to decrease as they are made smaller. Therefore, we developed a new sensing system that uses a hydraulic-driven micro device to measure the force applied to an object when it is held. This system can measure small forces acting on the tips of the end effector as the internal pressure changes. Generally speaking, pathological changes in living organisms can cause mechanical characteristics such as stiffness and viscosity to change. The palpations that a medical doctor performs are an example of this. Trained doctors can distinguish the state of an organ during an operation through touch. For robotic surgical systems such as *da Vinci,* the capability of distinguishing the state of the organ through touch will enable such a system to palpate. However, the relationship between mechanical characteristic changes and pathological changes must be explored for this to become a reality. We identified the mechanical characteristics of some viscoelastic materials similar to those used in a living organ. The hydraulic-driven micro device pushes an object and measures the reaction force and its displacement. Its stiffness and viscosity coefficient were obtained in calculations using *Kelvin-Voigt* and *Zener* models. Discrete displacement and load data were applied to the estimated model, and the mechanical characteristics of the materials were identified as a minimised value between the estimated value and the experimental one. In our experiment on viscoelastic materials, the value provided in the Kelvin-*Voigt* model was near the truth value. This report describes the identification methods and measurement results using these methods.

Sensor, Actuator, Hydrostatic, Accuracy

1. Introduction

Information and communication technology (ICT) has been increasingly utilised in medicine. Medical records are already computerised, and various information in medical procedures have been created as electronic data. Surgery in particular demands data on surgical operations for the introduction of robots . However, no method has been established in medical care to enable making data on living tissues for mechanical actions, which makes determining the mechanical characteristics of living tissues vital [1]. Therefore, we identified the mechanical characteristics of some viscoelastic materials similar to those used in living tissues. A hydraulic-driven micro device [2] pushes an object and measures the reaction force and its displacement. Its stiffness and viscosity coefficient were obtained in calculations using Kelvin-Voigt and Zener models. Discrete displacement and load data were applied to the estimated model, and the mechanical characteristics of the materials were identified as a minimised value between the estimated value and the experimental one. This report describes the identification methods and measurement results using these methods.

2. Model identification method

Generally, biotissue is thought to be a viscoelastic body. Because our device can measure the displacement and reaction force when it treats such biotissue, we try to express the mechanical characteristics of the biotissue using a combination of springs and dashpots. Two models were applied: the *Kelvin-Voigt* model of the simplest two elements and the *Zenner* model (the standard linear solid model) of three elements, ones which are more complicated than the elements of the *Kelvin-Voigt* model. Their fundamental equation is as follows.

$$\mathrm{F(t)} = \mathrm{k} \cdot \delta(\mathrm{t}) + \mathrm{c} \cdot \frac{\mathrm{d}\delta}{\mathrm{dt}} \quad (1)$$

The displacement $\delta(\mathrm{t})$ and the force $\mathrm{F(t)}$ which are measured for every sample using our device are discrete data. In the *Kelvin-Voigt* model, equation 1 is expressed as follows.

$$\mathcal{F} = \mathcal{A} \cdot \mathcal{p}, \quad (2)$$

where

$$\mathcal{F} = \begin{bmatrix} \int_0^{t_1} \mathrm{F}(\mathrm{t}_1)\mathrm{dt}_1 \\ \vdots \\ \int_0^{t_N} \mathrm{F}(\mathrm{t}_N)\mathrm{dt}_N \end{bmatrix}, \mathcal{A} = \begin{bmatrix} \delta(t_1) & \int_0^{t_1} \delta(\mathrm{t}_1)\mathrm{dt}_1 \\ \vdots & \vdots \\ \delta(t_N) & \int_0^{t_N} \delta(\mathrm{t}_N)\mathrm{dt}_N \end{bmatrix}, \mathcal{p} = \begin{bmatrix} c \\ k \end{bmatrix}.$$

The cost function *S* to be shown with equation 3 describes a measured value and the error with the parameter [3].

$$\mathrm{S} = \left\|\mathcal{F} - \mathcal{A}\mathcal{p}\right\|^2 \quad (3)$$

When partial differentiation is used in equation 3 and finds the minimum, the measured value and the error with the parameter are minimised. Thus, parameter *p* is identified as equation 4.

$$\mathcal{p} = (\mathcal{A}^T \cdot \mathcal{A})^{-1} \cdot \mathcal{A}^T \cdot \mathcal{F} \quad (4)$$

3. Sensing mechanism using hydraulic drive

The drive system of a hydraulic-drive mechanism is shown in Figure 1. The linear actuator uses a stepper motor that incorporates a ground ball screw. The linear actuator moves accurately by means of pulse control. The syringe plunger is moved perpendicularly using a linear actuator. The resolution of the water supply is 0.221 μl supplied by a syringe with a diameter of 15 mm. The force sensor is attached between the plunger and the actuator rod of the linear actuator. Internal pressure inside the syringe can be obtained because the force sensor measures the strength of force acting on the pruner. In consideration of noise, the force measurement resolution is ±37.1 mN. To decrease the end effector, we changed its cylinder from a bellows tube to a micro cylinder. Shrinking the cylinder structure was relatively easy because no transformation of the shell was required, unlike the bellows tube. Prototypes of the micro cylinder are shown in Figure 2. Micro cylinders with inside diameters of 1.64 mm were fabricated. The surface coarseness of the rod of a cylinder was fabricated in Ra1.6.

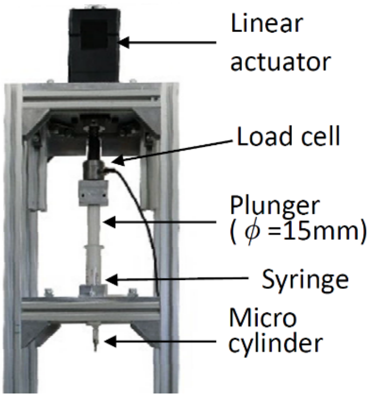

Figure 1 Hydraulic-driven mechanism.

Figure 2 Micro cylinder.

4. Measurement using hydraulic-drive mechanism

4.1. Target object imitating the biological tissue

The experiment object was a PVA gel mixed with borax, clear starch, and water. Table 1 shows the water ratio percentage of the target objects. Three types of gel having different hardness were made by changing the water content. Firstly, an experiment with a normal creep examination was conducted. A 2-gram thin plate of steel, 30 mm in diameter, was set over the target object so as to prevent any influence of the surface transformation. The transformation of the target object as it was set over a thin plate was photographed with a high speed camera at 120 FPS, and the displacement of the target object was provided using image analysis. Figure 3 shows the results of the creep test of the target object. The thin curve is a heteromorphic estimation. The heteromorphic curve of the No. 1 target is approximately equal to the estimated curve, and only part of the heteromorphic curve of No. 2 and No. 3 is off that of the estimated curve.

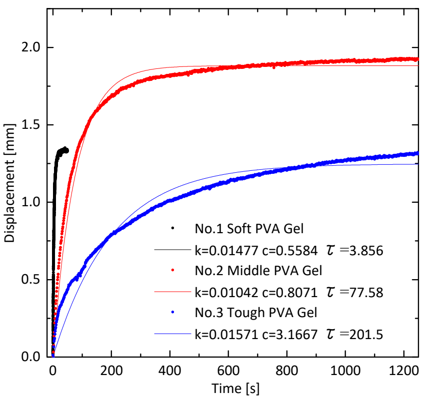

Figure 3. Creep test of target object.

Table 1 Target objects.

PVA Gel	Water ratio %
No. 1	72
No. 2	63
No. 3	54

4.2. Measurement experiment for identifying the object

Using the same object as in section 4.1, the sensing mechanism was measured using a hydraulic drive. The microcylinder was displaced from the state where the tip of the microcylinder contacts the upper surface of the target object and measures the reaction force. The supply flow to the microcylinder was 176.7 ml/s. The reaction force was provided from the fluid pressure change in the device, and the displacement of the fluid pressure in the device was estimated better than the quantity of the water supply. Because the estimate of the displacement included error, this experiment provided the displacement from the measurements obtained using the high-speed camera. The supply flow to the microcylinder was 176.7 ml/s. Figure 4 shows the results of the measurement reaction force and the displacement which was measured using the high speed camera and image analysis. Reaction force increased as the displacement of the microcylinder increased, and it kept a constant value after the cylinder stopped. The displacement of the target object increased as the reaction force increased, and its behavior resembled the results of the creep examination.

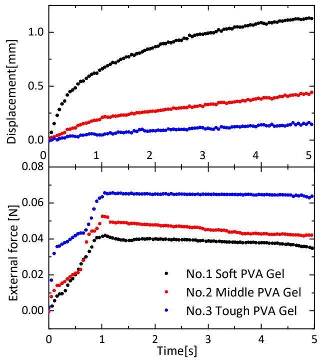

Figure 4. Results of measurement force and displacement.

Table 2 Identification values in experiment results.

PVA Gel	K [N/mm] (True value)	C [N/mm · s] (True value)
No.1	0.0393 (0.0148)	0.0129 (0.0569)
No.2	0.124 (0.0104)	0.102 (0.807)
No.3	0.480 (0.0157)	0.589 (3.167)

The identification value k measured with the sensing mechanism was near the value measured in the creep test. However, the identification value c differed from that found in the creep test. The reason for this difference was friction and water leakage caused in the micro-cylinder. As a result of having estimated the reaction force to be large, k slightly increased, and c generally decreased below the true value. Friction force was caused by surface roughness, and water leakage was caused by large clearance between the rod of the cylinder and the inside surface of the cylinder. Smaller clearance and less surface roughness in the cylinder are needed to measure the force with high precision.

5. Summary

We proposed methods for identifying the mechanical characteristics of living tissues. Their stiffness and viscosity coefficient were obtained in calculations using Kelvin-Voigt and Zener models. In our basic identification experiments using viscoelastic materials, the value provided in the Kelvin-Voigt model was near the truth value. In subsequent identification experiments using a hydraulic-driven micro device which pushes an object and measures the reaction force and its displacement, the stiffness slightly increased, and the coefficients of viscoelasticity generally decreased below the true value. The friction and water leakage of the micro cylinder caused this change. Further improvement in the device is necessary.

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