

Toward a Real Time Force Measurement by Vision

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Abstract

This paper discusses the way for estimating a contact force by high speed vision with a frame rate of 2[kHz]. We particularly focus on the estimation of a contact force through the deformation of a flexible beam. We show the basic working principle of the contact force estimation. We developed the experimental system for confirming the basic idea. By utilizing the system, we executed several experiments where the dynamics effects appear.

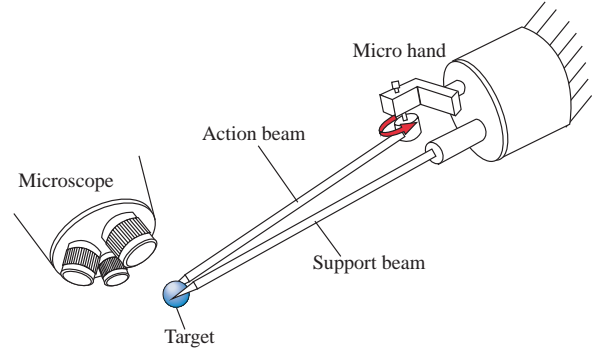


Fig.1: A view of micro hand

1 Introduction

The strain gauge is the most commonly used contact force sensor. The reasons why this sensor is widely used are that it has a very simple structure and keeps a high frequency response. However, there are couple of situations where it is hard to use it. For example, under a strong magnetic field, such as the case of fMRI(functional Magnetic Resonance Imaging). In such a case, there are alternative force sensors, such as a hand dynamometer using water pressure [1] or a force sensor by using an optical fiber where the loss of the light quantity depends upon how large the bending angle is [2]. Another case where it is hard to utilize a strain gauge would be a micro hand which can achieve a simple manipulation of a microscopic object, as shown in Fig.1, where two chopsticks like micro gripper is grasping a target object. For the force sensing in such a micro hand under the microscope [3], the displacement of an elastic beam by using a vision sensor is measured for estimating an equivalent contact force. Up to now, it has been restricted to force measurement only of a quasi-static condition because the response of processing speed of camera was as low as 30[Hz].

In this research, we propose the method which estimates the contact force in real time by measuring the displacement of an elastic deformation under dynamic condition using an online high speed vision system with a frame rate of 1[kHz] in the standard window.

Let us consider the case of a micro hand, as shown in Fig.1. The micro hand consists of a support beam and an action beam. As a simplified model for the

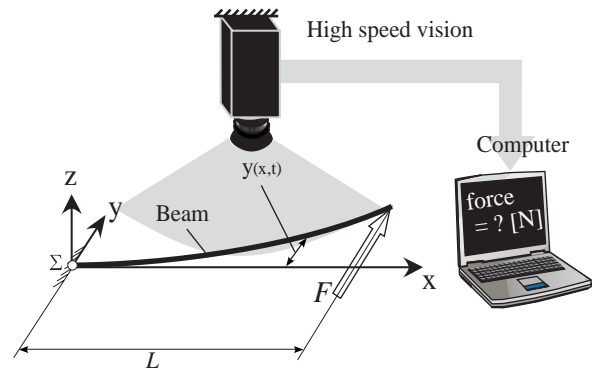


Fig.2: Conceptual image of vision based force sensing

micro hand, we regard it as a single beam, as shown in Fig.2. We consider the problem of estimating a periodic external force which acts at the tip of the beam. This paper is organized as follows. We refer to the related works in Chapter 2. A problem setup is performed in Chapter 3. In Chapter 4, after deriving a basic formula about the relation between the displacement of beam and contact force, we introduce a nondimensional parameter R which expresses the ratio of inertia force and the static bending force. We further show a method how to estimate the contact force. In Chapter 5, we verify the basic working principle of the introduced method by comparing the conventional approaches.

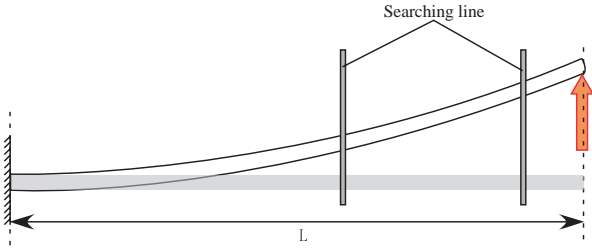


Fig.3: Explanation of searching line

2 Related works

There have been a couple of works where contact force is estimated by vision. Kaneko and others have proposed a system [4, 5] consisting an elastic beam and a vision sensor. They showed that both contact force and contact point can be estimated by measuring the displacement on two points of the beam. However, their system was limited to quasi-static condition where the change of motion is slow enough to ensure that any dynamic effect can be neglected.

As for vision sensors, Ishii and others developed the Mm(Mega-pixel and milli-second)Vision[6, 7]. The MmVision includes an intelligent pixel selection software which is able to find the center of gravity of an object with the frame rate of 1[kHz] in the standard window. However, within our knowledge, there has been no work discussing the dynamic based contact force estimation by utilizing an online high speed vision.

3 Problem setup

We suppose a beam whose shape in steady state is a straight line. Also let μ , E , I , and L be the mass per unit length, young's modulus, area moment of inertia, and the length of beam, respectively. We set the coordinate system as shown in Fig.2. The main assumption in this work are as follows.

Assumption 1: Attenuation of vibration by the viscosity of the beam can be neglected.

Assumption 2: The displacement of the beam is assumed to be so small, such that the movement of the contact point in the x-direction can be neglected, i.e. $y(L, t)/L < 0.1$.

Assumption 3: The movement of the beam is limited to planar motion.

Assumption 4: A periodic external force $F(L, t)$ excites the beam.

Assumption 5: Other frequency modes except the external force frequency can be neglected.

Under the above assumptions, we consider the simplified model shown in Fig.3, where we search for the center-of-gravity of the beam only along the shown searching lines. We treat the following problem.

Problem setup:

Suppose that an unknown periodic external force $F(L, t)$ is applied to the free end of the beam. Under this condition, answer the following questions:

- (1) How many searching lines are necessary and are sufficient to determine the shape of the beam?
- (2) How can we estimate the periodic external force?

4 Principle of estimation

4.1 General solution of bending equation

We consider the bending vibration of a beam for a given external force, as shown in Fig.3. The equation of motion of a small part of the beam can be expressed by the following equation [8].

$$EI \frac{\partial^4 y}{\partial x^4} + \mu \frac{\partial^2 y}{\partial t^2} = f(x, t); \quad (1)$$

$$f(x, t) = \begin{cases} 0 & (0 \leq x < L) \\ F(L, t) & (x = L). \end{cases} \quad (2)$$

Let us now define f_s and f_d as follows,

$$f(x, t) = f_s + f_d \quad (3)$$

$$f_s = EI \frac{\partial^4 y}{\partial x^4} \quad (4)$$

$$f_d = \mu \frac{\partial^2 y}{\partial t^2} \quad (5)$$

where f_s and f_d correspond to the forces generated by static bending and inertia forces, respectively. Supposing that the beam is under harmonic vibration, we can obtain the general solution by using the method of separation of variables

$$y(x, t) = Y(x) \cdot (A \cos \omega t + B \sin \omega t), \quad (6)$$

where

$$Y(x) = C_1 \cos\left(\frac{\alpha x}{L}\right) + C_2 \sin\left(\frac{\alpha x}{L}\right) \quad (7)$$

$$+ C_3 \cosh\left(\frac{\alpha x}{L}\right) + C_4 \sinh\left(\frac{\alpha x}{L}\right);$$

$$\alpha^4 = \mu L^4 \omega^2 / EI. \quad (8)$$

4.2 Introduction of nondimensional parameter R

When the periodic external force ($F_0 \sin \omega t$) is applied at the tip of the beam, f_s and f_d can be approximated as follows:

$$f_s \simeq EI \frac{y_{max}}{L^4}, \quad (9)$$

$$f_d \simeq \mu y_{max} \omega^2. \quad (10)$$

Let us now, define the nondimensional parameter R as follows,

$$R = \frac{\mu L^4 \omega^2}{EI} \quad (11)$$

where R expresses the ratio of inertia force and static bending force. As R increases, the inertia force also increases. Note that R exactly coincides with α^4 in Eq.(8).

4.3 Force estimation under quasi-static condition

In a quasi-static case, we can neglect the inertia force. By setting $f_d = 0$ in Eq.(3), the contact force $F(L, t)$ is given by

$$F(L, t) = \frac{3EI}{L^3} y(L, t). \quad (12)$$

4.4 Force estimation under dynamic condition

We suppose that the periodic external force ($F_0 \sin \omega t$) is applied at the end of the beam. At the fixed end ($x = 0$), the displacement and the bending angle are zero, i.e.

$$\begin{aligned} Y(0) &= 0, \\ Y'(0) &= 0. \end{aligned}$$

At the free end ($x = L$), the bending moment is zero and the shearing force has the same value as the periodic external force. i.e.

$$\begin{aligned} Y''(L) &= 0, \\ EI \cdot Y'''(L) \cdot (A \cos \omega t + B \sin \omega t) &= -F_0 \sin \omega t. \end{aligned}$$

We can determine all coefficients of eq.(7) under the above boundary conditions and obtain the contact force at the time $t = t_p$ is given by

$$\begin{aligned} F(L, t_p) &= y(x_v, t_p) \left\{ \frac{2EI\alpha^3 (1 + \cos \alpha \cosh \alpha)}{L^3} \right\} \\ &/ \left\{ (\sin \alpha + \sinh \alpha) \left(\cos \frac{\alpha x_v}{L} - \cosh \frac{\alpha x_v}{L} \right) - \right. \\ &\quad \left. (\cos \alpha + \cosh \alpha) \left(\sin \frac{\alpha x_v}{L} - \sinh \frac{\alpha x_v}{L} \right) \right\}. \quad (13) \end{aligned}$$

Applying the theorem of L'Hopital to eq.(13), we have the following relationship

$$\lim_{\alpha \rightarrow 0} F = \frac{3EI}{L^3} y. \quad (14)$$

Eq.(14) coincides with eq.(12). Finally, the answers to the problem setup in Chapter 3 are

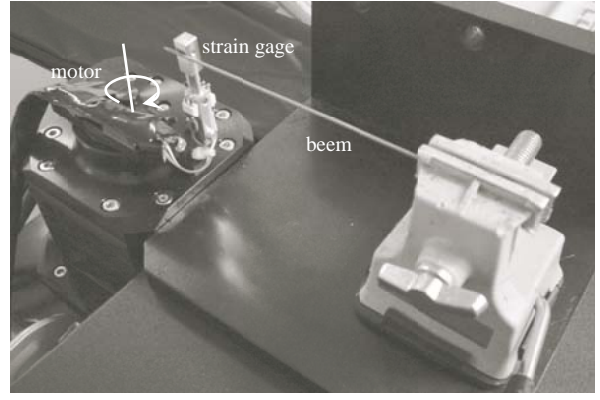


Fig.4: Experimental system

(1) One searching line is necessary and sufficient to determine the shape of the beam.

(2) We can estimate the periodic external force by eq.(13).

5 Experiment

5.1 The experiment method

The experimental setup is shown in Fig.4. The beam used in the experiment has the diameter of 1[mm] and the length of 110[mm]. Fig.5 shows the geometrical relationship between the beam and the force sensor stick. An arm is fixed to the axis of the motor. On the other end of the arm, the force sensor stick to which the strain gauge is attached, is fixed perpendicular to the arm. This arm is vibrated by

$$y = y_0 + y_1 \sin \omega t,$$

where $y_0 \geq y_1$. The displacement of the beam is measured at a particular point by the vision sensor. In this experiment, we use the MmVision (Photron) as a vision sensor, which can take frames with a resolution of 1024×1280 pixels and with the frame rate of 1[kHz] in standard window. In order to simplify the measurement, we use a white beam so that we can easily distinguish from the background. Fig.6 shows the way for measuring a point on the beam schematically. While the vision sensor has 1024×1280 pixels, we set the window of 1024×512 pixels as shown in Fig.6. Within the window, we focus only on one searching line with 1×512 pixels for detecting the displacement of the beam at one particular point ($x = x_v$). To search the center-of-gravity of the beam, we binarize the picture by setting up the threshold value against the 8 bit gray scale. As the beam moves by an external force, the center-of-gravity of the beam in the searching line also changes. In this experiment, x_v is fixed to the

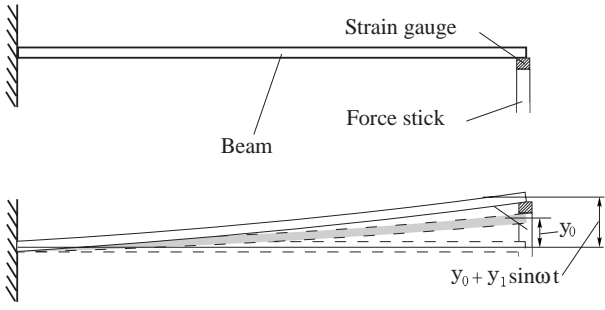


Fig.5: The geometrical relationship between the beam and strain gauge

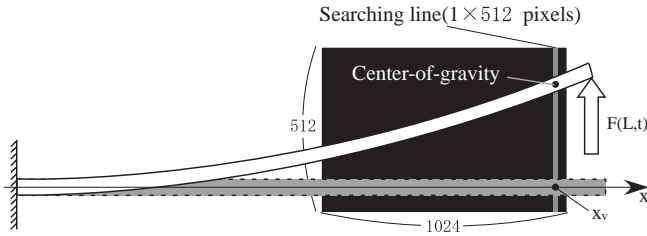


Fig.6: Explanation of searching line

distance 2[cm] from the tip of the beam. By measuring the center-of-gravity of the beam in the searching line, we obtain the displacement of the beam $y(x_v, t_p)$. The contact force is computed by using eq.(13).

5.2 Experimental results

Fig.7 shows the experimental results for $R = 0.0001, 0.0021, 0.15,$ and $0.21,$ respectively. Fig.8 shows the experimental results for $R = 0.15$ and 0.21 with a scale change with respect to time. Each figure shows the force measured with the strain gauge, the force estimated by the introduced method, and the force estimated by the static method (eq.(12)). When R is small, these figures show that the force estimated by all methods nicely agree with the measurement by strain gauge. As R increases, the force estimated by static method differ from two other methods, while both the introduced method and strain gauge based one still keep a nice coincidence.

6 Conclusion

This paper proposed an approach for estimating the contact force between a flexible beam and an environment by a high speed vision. The proposed approach made it possible to estimate the contact force by using just one searching line. The approach enabled us to estimate the contact force with the sampling rate of 2[kHz]. We confirmed that the approach could successfully estimate the contact force.

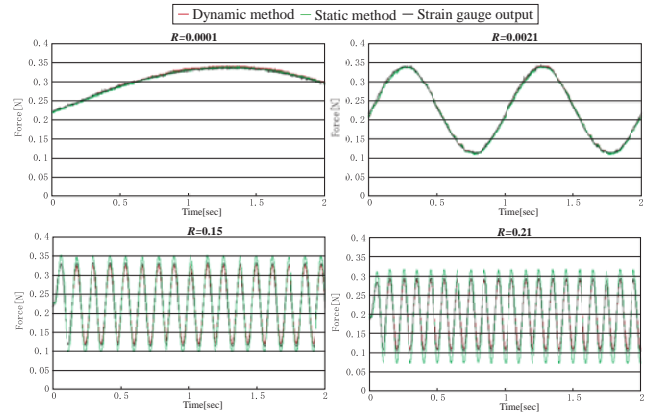


Fig.7: Experimental results (2[seconds])

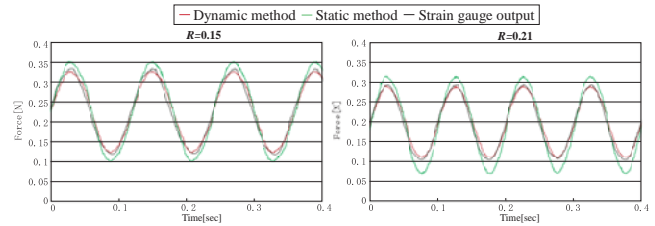


Fig.8: Experimental results (0.4[seconds])

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