Precision Sensors, Actuators and Systems

Precision Sensors, Actuators and Systems

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PRECISION SENSORS, ACTUATORS AND SYSTEMS

SOLID MECHANICS AND ITS APPLICATIONS
Volume 17

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Aims and Scope of the Series

The fundamental questions arising in mechanics are: *Why?*, *How?*, and *How much?* The aim of this series is to provide lucid accounts written by authoritative researchers giving vision and insight in answering these questions on the subject of mechanics as it relates to solids.

The scope of the series covers the entire spectrum of solid mechanics. Thus it includes the foundation of mechanics; variational formulations; computational mechanics; statics, kinematics and dynamics of rigid and elastic bodies; vibrations of solids and structures; dynamical systems and chaos; the theories of elasticity, plasticity and viscoelasticity; composite materials; rods, beams, shells and membranes; structural control and stability; soils, rocks and geomechanics; fracture; tribology; experimental mechanics; biomechanics and machine design.

The median level of presentation is the first year graduate student. Some texts are monographs defining the current state of the field; others are accessible to final year undergraduates; but essentially the emphasis is on readability and clarity.

For a list of related mechanics titles, see final pages.

PREFACE

Research and development of high-precision systems, micro electromechanical systems, distributed sensors/actuators, smart structural systems, high-precision controls, etc. have drawn much attention in recent years. These new devices and systems could bring a new technological revolution in modern industries and further impact future human life. This book is concerned with the most updated new technologies in this general area, such as silicon based sensors/actuators and control, piezoelectric micro sensors/actuators, micro actuation and control, micro sensor applications in robot control, optical fiber sensors/systems, etc. There are four essential subjects emphasized in this book: 1) surveying the state-of-the-art research and development, 2) tutoring fundamental theories and tools, 3) demonstrating practical applications, and 4) discussing future research and development.

The first part of this book was used as teaching materials for a Tutorial on High-Precision Sensors/Actuators and Systems and the second part for a Tutorial on Smart Piezoelectric Systems at the 1992 and 1991 IEEE International Conferences on Robotics and Automations, respectively.

The editors would like to express their deepest appreciation to all contributors who made the above tutorials and thereafter this book successful.

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Mechanics

SOLID MECHANICS AND ITS APPLICATIONS

Series Editor: G.M.L. Gladwell

Aims and Scope of the Series

The fundamental questions arising in mechanics are: *Why?*, *How?*, and *How much?* The aim of this series is to provide lucid accounts written by authoritative researchers giving vision and insight in answering these questions on the subject of mechanics as it relates to solids. The scope of the series covers the entire spectrum of solid mechanics. Thus it includes the foundation of mechanics; variational formulations; computational mechanics; statics, kinematics and dynamics of rigid and elastic bodies; vibrations of solids and structures; dynamical systems and chaos; the theories of elasticity, plasticity and viscoelasticity; composite materials; rods, beams, shells and membranes; structural control and stability; soils, rocks and geomechanics; fracture; tribology; experimental mechanics; biomechanics and machine design.

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Mechanics

FLUID MECHANICS AND ITS APPLICATIONS

Series Editor: R. Moreau

Aims and Scope of the Series

The purpose of this series is to focus on subjects in which fluid mechanics plays a fundamental role. As well as the more traditional applications of aeronautics, hydraulics, heat and mass transfer etc., books will be published dealing with topics which are currently in a state of rapid development, such as turbulence, suspensions and multiphase fluids, super and hypersonic flows and numerical modelling techniques. It is a widely held view that it is the interdisciplinary subjects that will receive intense scientific attention, bringing them to the forefront of technological advancement. Fluids have the ability to transport matter and its properties as well as transmit force, therefore fluid mechanics is a subject that is particularly open to cross fertilisation with other sciences and disciplines of engineering. The subject of fluid mechanics will be highly relevant in domains such as chemical, metallurgical, biological and ecological engineering. This series is particularly open to such new multidisciplinary domains.

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CONTENTS

New Actuators for High-Precision Micro Systems

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ABSTRACT

Since micro manipulation is necessary for the handling of the micro order small objects, actuators suitable for a micro manipulator have long been desired. This paper proposes a simplified structure of the new electrostatic actuator with multi degrees of freedom(3 DOF and 6 DOF), which is different from the conventional ones. For the dexterous manipulation, versatile skillful motions are required and this can be easily accomplished by using the proposed micro actuator. In this study, a prototype of this micro electrostatic actuator is produced. In this paper, the nonlinear dynamics of this actuator is modeled, then the position control simulations are carried out with the proposed nonlinear feedback control method. Design method and experimental position control results of the prototype micro actuator are also shown for the discussion. Moreover, we introduce the optical actuator which has advantages of (i) non-contact control and (ii) control signal transmission. These advantage will become important for the next actuators for the high-precision micro systems.

1. INTRODUCTION

Many types of small sized manipulators/1,3,4,5,8,15,16/ and micromechanical systems/2/ have recently been developed in many fields. These manipulators are required to clamp or to contact with very small objects, such as a living cell of creatures or parts of the semiconductor electronics. We have studied a bilateral control methods of micro manipulators and visual recognition method of objects for the micro manipulation/5,6,7/.

There are two different ways to clamp a small objects, i.e.,one is to clamp them by a

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conventional relatively large sized manipulator with a precise control system, and the other way is to miniaturize a manipulator itself, adapting itself to the small objects. Comparing these ways with each other, we came to conclude that a small sized manipulator is convenient in the point that can be used in a narrow space. Therefore, we have miniaturized manipulators itself and have made two different types of manipulators; one with a piezoelectric actuator/5/ and the other with an electrostatic actuator/8,15,16/.

As an actuator, a piezoelectric type is appropriate to the stabbing control of penetrating small stick type tool to the membrane of cells/4/, because of its quick response. But in the point of miniaturization, it has the structural limitations around millimeter range. To achieve further miniaturization of a manipulator, the actuator itself must be miniaturized. The electrostatic actuators, which have already been reported/8/, are appropriate in this point of view.

This paper proposes a simplified structure for the new actuator with multi degrees of freedom(3 DOF/8,15/ and 6 DOF/16/), which is different from the conventional types/2,3,4/. For the dexterous manipulation, versatile skillful motions are required and this can be easily accomplished by the proposed structure. In this study, a prototype of this micro electrostatic actuator is produced. The structure of this actuator is suitable for the photo etching process, and it has the possibility to be miniaturized much smaller, in the future/9,12,13/.

In the study fields of the microactuator, there are quite few study work on a model based dynamic control method. This paper describes the modeling of the proposed microactuator. The position control simulations are carried out with the proposed nonlinear feedback control method. Design method and experimental position control results of the prototype micro actuator are also shown for the discussion.

Most of these actuators utilize electric energy to actuate and control itself. Recently, optical actuator, which can be operated by optical energy sources, have been reported. This kinds of actuators have advantages as follows; (i) Non-contact control is possible, and (ii) It is free from electromagnetic noises. Especially, an optical actuator using optical piezoelectro element, which has photostrictive phenomena, attracts us very much, because (iii) it has characteristic of transforming optical energy to mechanical displacement directly. In this paper, we introduce some characteristics of this actuator.

2. PRINCIPLE OF ELECTROSTATIC MICRO ACTUATOR

2.1 Basic Principle 1

If some voltages are applied between a couple of conductive plates shown in Fig.1(A), it is well known that electric charge is stored between the plates. This potential attracts these plates each other. This force F is called the electrostatic force, and is calculated as follows:

$$F=\frac{\varepsilon S}{2}\left(\frac{V}{d}\right)^2 \qquad (1)\text{-A}$$

F: electrostatic force
ε : dielectric constant
S: area of the electrode
V: applied voltage
d: distance between electrodes

Analyzing the above equation dimensionally, we can easily understand the advantageous reason of miniaturizing electrostatic actuator/10,11/. Assuming applied voltage is constant and considering the dimension of length is [L], we can calculate the ratio of the output per one unit of volume as follows.

$$\frac{Fl}{l^3}=A\frac{Sl}{d^2l^3}\ \frac{[L^2][L]}{[L]^2[L]^3}=\frac{1}{[L^2]} \qquad (2)$$

where, $A=\frac{\varepsilon V^2}{2}$.

Hence, the output per one unit of volume is inversely proportional to the square of the length. This means that the electrostatic force per one unit of volume becomes larger as its body becomes smaller. So, we can conclude that the electrostatic actuator is more advantageous in smaller size.

2.2 Basic Principle 2

When a couple of conductive plates are placed and shifted by X(Fig. 1(B)), thrust force Ft arises between the plates in addition to the attractive vertical force. Thrust force is calculated by integrating the potential energy and differentiating it with x. The first approximation is shown in eq. (1)-B.

$$F_t = \varepsilon_0 \cdot \varepsilon \cdot \frac{WV^2}{2d} \qquad (1)\text{-B}$$

where W is the width of the electrode.

3. MODELING AND DYNAMICS OF 3 DOF ELECTROSTATIC MICRO ACTUATOR

3.1 Moving Modes

To make a small actuator with multiple degrees of freedom, the structural design of the microactuator is important. Here we propose the structure of the microactuator in Fig. 2 to meet this requirement.

Figure 3 shows the moving modes of this microactuator. The tip of the probe moves in the different direction in accordance with the applied voltage at each electrodes; no. 1, 2, 3 and 4. It is easily understood that the three different types of basic moving modes can be generated. "Mode 1" is a rotary motion of the probe tip around the Y axis. This can be attained as follows. At first, voltages are applied to the electrodes No. 1 and No. 2 equally. Then these voltages are switched to be applied at the electrodes No. 3 and No. 4. Then, switching these applied voltages again to the electrode No.1 and No. 2 and repeating this process, we can produce Mode 1. "Mode 2" is a rotary motion around the x axis. Likewise, applying voltages to the electrodes No. 2 and No. 3 equally, and switching these applied voltages to the electrodes No. 1 and No. 4, we can produce Mode 2. In the same way, applying voltages to the all electrodes equally, and switching them to the different level, a traveling motion can be generated in the z direction, which is called "Mode 3".

3.2 Characteristics

The model of the actuator is shown in Fig. 4. A base coordinate system is set at the center of the stator electrode. The coordinate system of the movable electrode is set parallel to the Z direction at the distance of c from the base coordinate system.

Now, we consider the relationship between the electrostatic force Fv and the restoring force Fk of the suspension spring which holds the movable electrode. Figure 5 shows the relationship between the displacement x and the generated electrostatic force Fv on each supplied voltage, and the relationship between the displacement x and the restoring force Fk of the suspension spring.

Here we think the case that the primary distance between the stator electrode and the movable electrode is 100 micrometer, and the applied voltage is less than 300 v, and as in Fig. 5, the electrostatic force curve (Fv curve) comes in contact with the restoring force line (Fk line) at the applied voltage of 300 v.

In Fig. 5, the intersection of the Fv curve and the Fk line means that at that voltage and displacement, " Fv = Fk " is realized and these forces are balanced. For example, when the applied voltage is 200 v, there are 2 points, that is , the points around x = 10 μm and 67 μm where these forces are balanced. In this case, these points are apart from each other, so they do not affect each other. But in the case that the applied voltage is around 300 v, the stable points around x = 33 μm are close to each other, and they have possibility to affect each other at that applied voltage. This will degrade the stability of the position control. Moreover, if the voltage is applied over 300 v, the system becomes unstable. We should apply the voltage less than 300 v.

In addition, the difference between the Fv curve at 300v and the Fk line implies the maximum attraction force by the electrostatic actuator at that displacement. Therefore, the electrostatic actuator cannot exert any force to the objects around the applied voltage of 300 v.

3.3 Calculation and Design of Mechanical Characteristics

Next, we calculate the elastic constants of the spring which supports the movable electrode (Fig. 2-3). In Fig. 5, the gradient of the Fk line implies the elastic constant. When we set the Fv curve contact with the Fk line at the possible maximum voltage, we can make the working range of the actuator wide while preserving the capability to exert force