

Paper:

# Development of Microscopic Hardness and Stiffness Investigation System with MicroRobot

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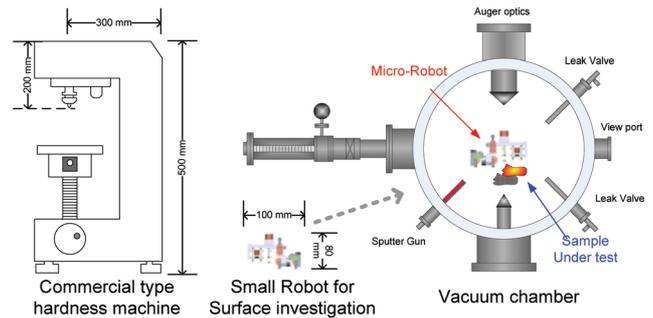
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In order to investigate micro hardness and stiffness in a special chamber, the development of a small-force generator mechanism and a piezodriven microrobot is described in this paper. This small-force generator is simply composed of a Voice Coil Actuator (VCA) and the tandem leaf spring mechanism. The small force can be controlled by an electrical current, which is supplied to the coil and positioned precisely at the balance point with the parallel leaf spring with no mechanical friction. The full bridge strain gauges on both sides of the double leaf spring can detect a small force that is applied to the sample with a microindenter. This handmade small device can produce and verify small forces up to 17 mN with good linearity and a 50  $\mu$ N resolution. The displacement of the indenter head can be also measured by the Linear Valuable Differential Transformer (LVDT) on the machine for monitoring the depth behavior of the indenter during the whole dwell time. The small force generator with the indenter can be implemented on the piezodriven microrobot to check the microscopic hardness and stiffness. This microrobot can move around the measurement area precisely step by step with 1  $\mu$ m steps on a metal plate, so that the sample can be scanned with microscopic resolution in situ, such as in an SEM chamber. In the experiment results, the basic performance of microelasticity investigations with a certified hardness block was successfully checked and the indentation load-depth characteristics were precisely acquired on the path of the microrobot.

**Keywords:** voice coil actuator, tandem leaf spring mechanism, strain gauge, inchworm microrobot, microindenter

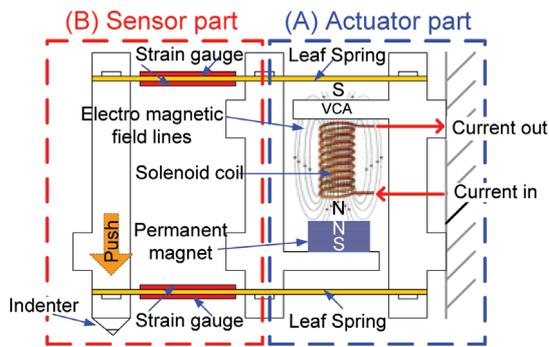
## 1. Introduction

For 100 years, the hardness test have been widely used to determine strength of material as non-destructive test method. Because the indentations are small enough not to destroy or effect to surface quality of material under test. One of the most useful hardness testing methods is the well-known Instrumented Indentation hardness Test (IIT). The hardness test consists of pressing an indenter with known geometry and mechanical properties under prede-



**Fig. 1.** Approximate size comparison between the commercial type hardness machine and the original micro surface investigation robot. The robot aims to operate inside a small chamber.

defined conditions against the test material. Here the predefined conditions are the controlled testing time and testing force. In order to perform the microhardness test, the loading force of the indenter should be precisely applied to the material without any shock or vibrations. There are a number of mechanisms and methods for nano- and microrange force generators, and one method is widely used in nano-indentation machines. In 1981, the most common means of applying force – by using a coil of wire inserted into a cylindrical slot in a permanent magnet – was introduced [1], and in 1995 the method of force generation by using electrostatic force actuation was proposed [2]. Another researcher employed a spring method [3,4]. Each method has its distinct advantages and disadvantages. Recently, many commercial nano-indentation machines [5–7] have been available in the market. However these machines come with huge structures that cause thermal drift as well as cost problems. In terms of thermal drift change in the machine frame dimensions, in **Fig. 1**, the typical size of the commercial machine is approximately 500 mm in height and 300 mm in arm length; the machine is made of some metals. Then with a 1°C temperature change, the uncertainty is about 5  $\mu$ m. Thus these machines should be installed in a special temperature-controlled room, where the temperature change is less than 0.1°C. The size of our small robot is approximately 2 cubic inch, and the measurement uncertainty might be less than 0.5  $\mu$ m even for a temperature change of 1°C. Generally speaking, when the size of the machine becomes one tenth, consequently,



**Fig. 2.** Design of the VCA associated with a tandem parallel leaf spring: the actuator part (A) and the sensor part (B).

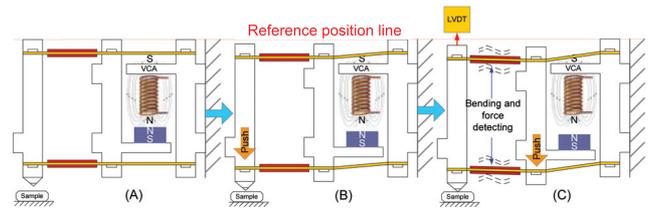
uncertainty from the thermal effect can be expected to be one-tenth. Furthermore in the case of biological applications or some other kinds of applications that require a special chamber, most commercial machines are too large to be implemented in a small chamber.

Recently microrobot technologies have become well known; microrobots have fine mobility with microscopic resolution and can work in small areas [8–11]. As the first step in this research, we focus on fabricating a microhardness and stiffness measuring system with a couple of downsized instrumentation designs and microrobotics. In our final application, this unique measurement system with very small body and high mobility can be employed for purposes such as performing micro-investigation in a special chamber as shown in **Fig. 1**. To clarify this concept, the combination of the microhardness and stiffness machine and microrobot is described. The first part is the microforce generator machine which is composed of the VCA and parallel leaf spring mechanism. The main structure is composed of tandem parallel springs with an electro-magnet and double strain gauges. It can generate small forces up to 17 mN with good linearity and a  $5 \mu\text{N}$  resolution. This microactuator is an important part for the development of the microhardness and stiffness machine in this research. The second part is a piezodriven inchworm microrobot. This inchworm microrobot can achieve highly precise scanning movement with a step less than  $1 \mu\text{m}$  [12].

The microforce generator with the indenter and sensors (the third part) is implemented on this small robot so that it can detect microsurface hardness and stiffness characteristics along the path of the robot. In this paper, we describe a unique testing system for micro hardness/stiffness constructed using microrobotics. Here the experimental results with such reference hardness block will be given. This can indicate the potential performance of this measurement system.

## 2. Microforce Generator with Voice Coil Actuator and Tandem Parallel Spring

In this section, we are proposing the original handmade microforce generator in order to give a small force to the



**Fig. 3.** (A) Machine operation in the initial state. (B) Indenter is approaching the sample by the VCM. (C) The indenter is in contact with and penetrating the sample, and the applied force and indenter depth are measured.

indenter. This is built from a VCA technique associated with a tandem parallel leaf spring. The parallel leaf spring mechanism can produce the rectilinear displacement of the platform without any friction. At first, the design of microforce generator and its basic performance are described. The layout of the VCA associated with the tandem parallel leaf spring is shown in **Fig. 2**. It is composed of two parts: the actuator part (**Fig. 2(A)**) is a VCA that is implemented with a parallel leaf spring and the sensor part (**Fig. 2(B)**) is also a parallel leaf spring with strain gauges and an indenter. This layout can allow a small precise displacement to the indenter as well as detect the force applied to the indenter so that the depth-force curve can be characterized.

### 2.1. Actuator Part

The actuator part that can give a microdisplacement consists of two L-bars and two parallel leaf springs. They are assembled as shown in **Fig. 2(A)**. The solenoid coil is set on the top side of the frame and the permanent magnet is set on the bottom side. This layout is well known for a VCA. The magnetic fields are produced by electric currents. An electric current carrying conductor in a magnetic field produces a force perpendicular to the direction of the electric current and the magnetic field. The generated force depends on the length of the conductor in the magnetic field and the electric current. In this actuator, the turn number of the solenoid coil is important as it should generate an appropriate force enough to activate the parallel spring in the required range. Here the repelling action between the permanent magnet and solenoid coil is used. Thus it is possible to control the magnetic force with the electric current applied to the coil and the parallel leaf spring can be deformed to balance the spring force with the electromagnet in the initial state as shown in **Fig. 3(A)**. Then when the electric current is increasing, the magnetic field will push the coil and the attached VCM arm downward as shown in **Fig. 3(B)**. The parallel leaf spring mechanism made by phosphor bronze can produce the rectilinear displacement of the platform. There are the forces sensing elements, which are connected as the full bridge four strain gauges have been bonded on both sides of parallel leaf spring as shown in **Fig. 2(B)**. When the indenter tip is in contact with the surface of the sample, the bending action of the parallel leaf springs and the indenter depth can be monitored from the strain gauge