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COMPACT MICRO FORCE GENERATOR WITH TANDEM LEAF SPRING AND VCA ON MICRO ROBOT FOR MICRO HARDNESS AND STIFFNESS TEST.

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Abstract – This paper presents the development of compact size force generator mechanism with voice coil actuator and piezo driven micro robot for surface hardness and stiffness investigation. This small force generator is composed of voice coil actuator and tandem leaf spring mechanism. The small force can be controlled by electrical current which is supplied to coil and positioned precisely at the balance point with the parallel leaf spring with no mechanical friction. And the full bridge strain gauges on both side of double leaf spring can detect small force which is applied to the micro indenter. This unique layout can provide good linearity and small force up to 20 mN with 0.05 mN resolution. The displacement of the indenter head also can be measured by the laser displacement sensor for monitoring the depth behaviour of the indenter during whole dwell time. Since the overall size of this force generator is compact enough to implement on the piezo driven micro robot, it can be possible to employ them in such the SEM chamber for in-situ measurement.

In the primary experiment, the performance of small force generator unit is compared with the hardness standard block at first and then the surface hardness distribution is investigated with the help of the micro robot as it can transport the sample material precisely with 1 μm resolution.

Keywords: voice coil actuator, tandem leaf spring mechanism, strain gauge, inchworm micro robot, micro indenter.

1. INTRODUCTION

There are many designed mechanisms and methods to complete nano and micro range force generator, the soft load controlled machines is one methods widely use for nano-indentation machines. In 1981, the most common means of applying force by using a coil of wire is inserted into a cylindrical slot in a permanent magnet was introduced [1], In 1995, the method of force application by using electrostatic force actuation was proposed [2], another researcher uses the application of load through a spring method [3]. Nowadays, many companies have developed their own commercial nano-indentation machine [4], [5],

[6]. But in the market these machine price is very high and come with huge size overall structure. Therefore, it is not possible for university or research laboratory to have own nano-indentation machine. Anymore in case of biology application or some application that operate inside special chamber, most of them are larger to implement in the small chamber.

As the first step is focusing to make the micro hardness and stiffness measuring system which can provide the down-sized design and cost reduction. At this point is proposing the micro force generator that is composed of a tandem parallel spring with the electro-magnet and double strain gauges. It can provide linear displacement generated with high resolution force measurement. And with high precise movement in 1 $\mu\text{m}/\text{step}$ of the piezo driven micro robot which easily measurement even for the application inside small chamber. In this document described proposing and designing for the unique testing system for micro hardness/stiffness.

2. MICRO DISPLACEMENT GENERATOR MACHINE

2.1. Design and concept

As shown in figure 1, the micro displacement generator machine consists of two frames (L-bar) supported by parallel leaf spring. There are solenoid coil placed on the top side of L-bar, down side is permanent magnet. This layout is well known as “voice coil actuator” (VCA). It is use as displacement actuator in this machine. The magnetic fields are produced by electric currents, which electric current carrying conductor in a magnetic field will produces a force perpendicular to the direction of the electric current and the magnetic field. The magnitude of the force depending on the length of conductor in the magnetic field and electric current supply. In this mechanism the solenoid coil fabricated from copper wire with 0.2 mm diameter in 200 turn wired, that can generate force enough to actuate the parallel spring with the smallest size. Magnetic field sources are essentially dipolar in nature, having a north and south magnetic pole. In this machine, the action between permanent magnet and solenoid coil is pushing direction (North Pole to North Pole, South Pole to South Pole). The amount of the electric current

applied is means of controlling the magnetic force produced. Programmable power supply (HP-6632A) use as is a current control source. The electric current supplied was limited in 0.5A, due to temperature product from high current supply can disturbed to another sensing part.

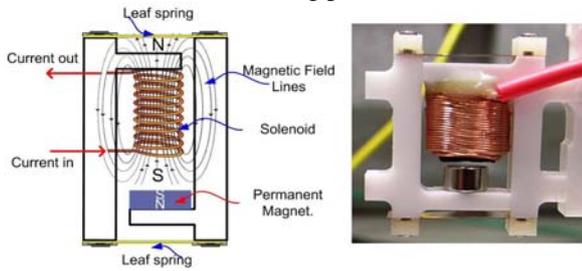


Figure 1. Structure of micro displacement generator.

The phosphor bronze 50 um thin plate is used as leaf spring. This simple parallel leaf spring mechanism can produces rectilinear displacement of platform. Even though the rotation of cantilever and bending moment of platform effect to position of generated displace, but this error can be compensated by limit displacement of moving arm. As the movement is very small displacement we may can negligible this problem [7].

2.2. Displacement generated performances test

In the experimental, when DC current was supplied to coil at 0.5mA per step, the VCA has response to current at 1.5mA step. Then current step input was limited at 1.5mA per step as the smallest current supplied that can move L-bar arm or best resolution of this machine. This performance test was supplied DC current 1.5mA per step increase from 0 until 0.5A after that decrease 1.5mA per step down to 0A. The behaviour of moving L-bar arm as a result of current supplied was investigated by laser displacement sensor. Then resolution, linearity and operation range of micro displacement generator machine was checked precisely as shown in figure 2 and 3. From the experiment results has shown that, this machine can generate displacement up to 280 um with 0.5A current supply. The resolution result shows displacement 1 um at 1.5mA step current supply. The linearity graph shows completely same behaviour of increase and decrease generated displacement.

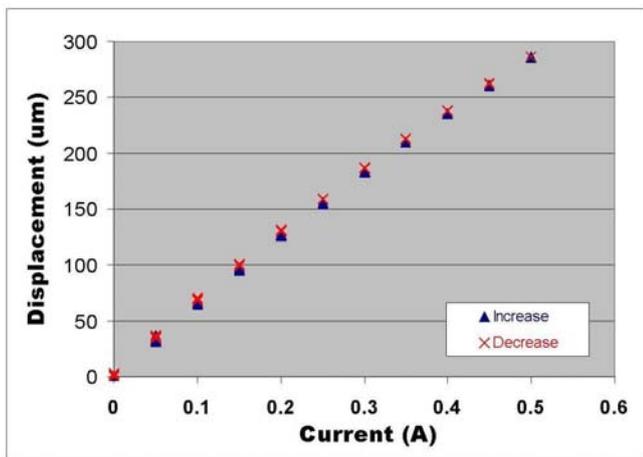


Figure 2. Experiment results with the displacement of the paralleled spring driven by VCA.

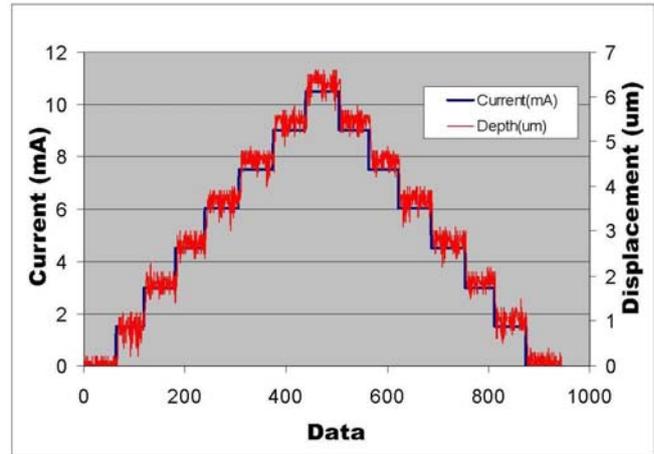


Figure 3. Experiment results with the step response to the input current.

3. MICRO FORCE GENERATOR MACHINE

3.1. Force sensing element

From figure 4 it is shown that the force sensing element attached on the leaf spring. By bonded full bridge strain gauge on both side of parallel leaf spring, the bending action of parallel leaf spring can be monitored. Resistance change of sensing part due to bending action of leaf spring was magnified 200 times by bridge amplifier.

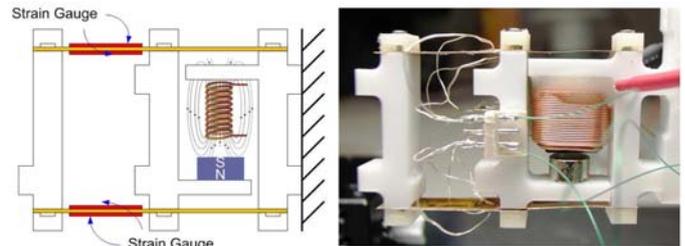


Figure 4. Force sensing element attached.

Then voltage output from amplifier circuit was read out by six and a half digits multi meter. The force sensor element work as a feed back signal, the force value can be generated from displacement change of L-bar arm of force generator machine and the expected force can be measured and limited by force sensing feed back signal. After attached force sensing element then performance tested of machine was done by using laser displacement sensor for observes displacement change and 50mN standard load cell was used for measure the generated force. The machine calibration and adjustment was done in this section. The experiment results on figure 5 shows that, the generated force in both sides (increase and decrease direction) have good linearity with less hysteresis by maximum current supply at 0.5A. In this case output from force sensing element is voltage was compared with milli-Newton force value from load cell. From figure 6 shows resolution of generated force at 50 μN and good repeatability by 20mA step current supply increase and decrease direction. From the results in the figure 6 has shown less vibration signal of generated force, even at one resolution (50 μN). Which means the micro force machine shows good ability to generate soft load controlled without any shock or impulse attack. This force machine be able to used for generate force in hardness machine.

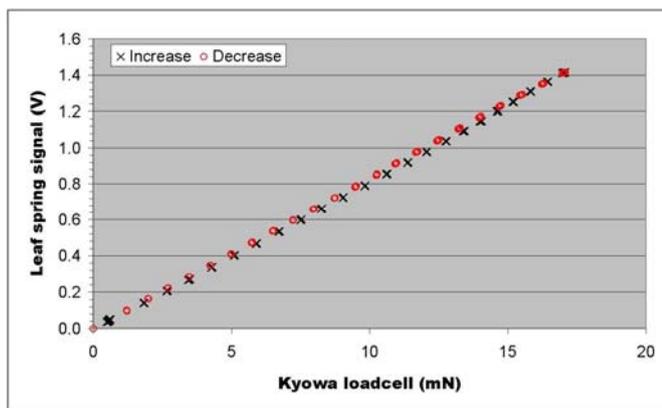


Figure 5. Experiment results with the relation between the generated force and the displacement.

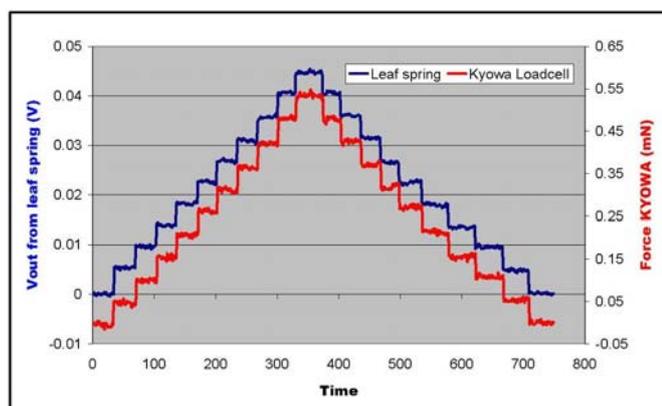


Figure 6. Experiment results with the resolution of the generated force.

3.2. Piezo driven micro robot stage carrying

The unique small robot driven by the piezo elements can work within the length of micro meter resolution has been developed in 2000 [8]. Figure 7 shows the diagram and real picture of micro inch-worm robot, it has dimension in 30mm wide 5 mm long and 3 mm height. The small robot consisted of the piezo elements and electro magnetic legs for providing the accurate inch-worm locomotion by supply AC voltage to piezo element simultaneously with magnetic legs coil current control.

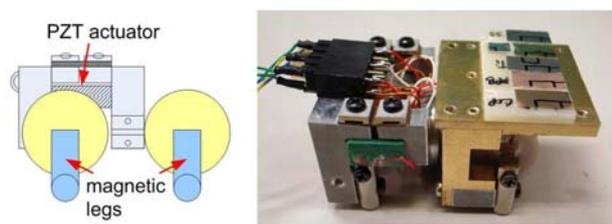


Figure 7. Inch worm micro robot.

By supply 2 VAC per step to piezo element; this locomotion movement has step response about 1µm per step for forward direction and about 3.5 µm per step for reverse direction. It has good repeatability even movement without guidance or feed back control. The repeatability of movement of robot depends on ground surface and carrying weight. The stage sample holder is placed on the top of robot. It can carry sample under test to the measurement position and doing profile surface measurement test.

4. MICRO HARDNESS MACHINE

Now, the machine can be implementing in to micro hardness machine. In figure 8, the overall of micro hardness measurement machine is shown. Regarding to martens hardness [9], it is measured under applied test force which defined for pyramidal indenter not defined for the Knoop indenter or ball indenter. But in case of this mechanism, due to small size and light weight of surface roughness stylus tip (cone angle 60°, tip radius 2µm), it is attached at the top of pressure plate as indenter of hardness machine. The laser displacement sensor is used as depth measuring device can be monitoring indentation depth during whole dwell time. And the micro stage piezo driven inchworm micro robot for carrying the test sample to be measured. Measurement results and machine operation including micro force machine and micro robot was control by computer.

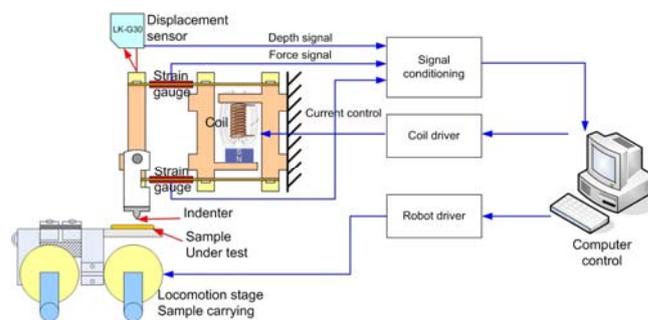


Figure 8. Micro hardness measurement system.

4.1 Experiment on certified hardness block

After successful in measurement system and control system of machine, next is experiment on indentation on certified hardness block. In the experiment, 30HV and 100HV certified hardness block is used as unit under test. These two hardness blocks was certified by 10gf lowest force (testing force is 1kgf, 0.1kgf and 0.01kgf). By making an indentation with three level of testing force 5mN, 10mN and 15mN on surface of both hardness blocks, the elasticity of blocks was investigated by the indentation load-depth curve. In the experiment, controlling force application and force removal time are 30s. The holding time at maximum force is 30s. The experiment results on figure 9 and 10 show the indentation load-depth curve on 30HV and 100HV respectively. By using colour laser interference microscope, the indentation 3D profile was investigated and shown in figure 11. Diameter of each indentation on each force was measured and compared with the maximum depth from load-depth curve as shown in table 1. From 3D profile of indentation on 100HV with 10mN show elliptic print dimension, which means limited of machine performance. Because of this tiny machine is used 50µm phosphor bronze sheet as leaf-spring to hold all structure together, this leaf-spring might be caught of problem. The main structure can not with stand 10mN test force on harder surface. The geometric of indenter print is changed due to the rotation of cantilever when indenter can not penetrate in harder surface. So, from this issue we make a decision to limit operation range of this machine at 10mN test force on surface that softer than 30HV, to avoid damage of moving part of this machine.

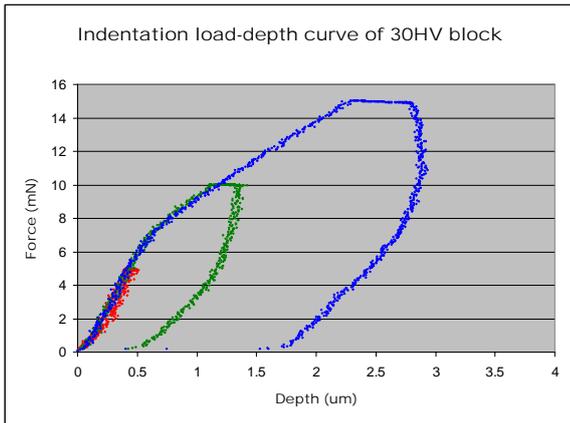


Figure 9. Indentation load-depth curve of 30HV certified block at 5mN, 10mN and 15mN testing force.

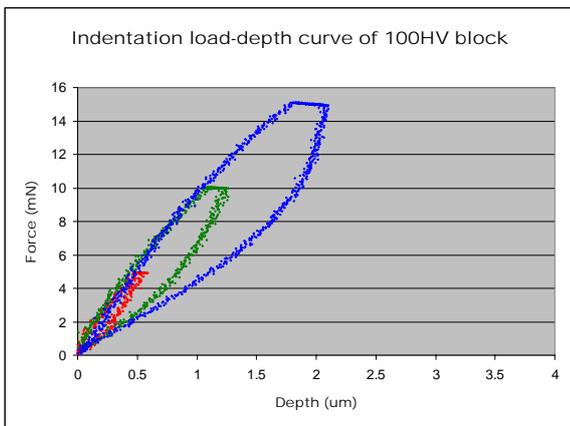


Figure 10. Indentation load-depth curve of 100HV certified block at 5mN, 10mN and 15mN testing force.

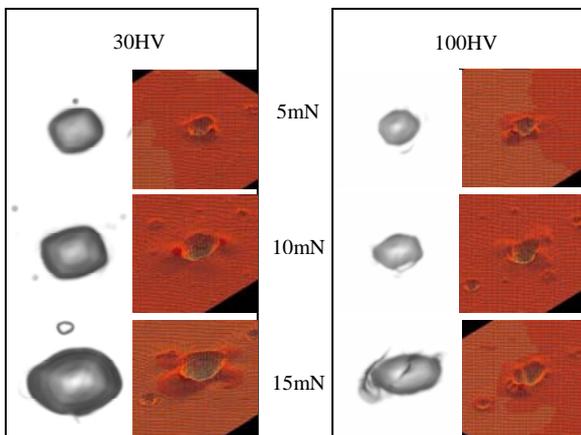


Figure 11. Indentation 3D profile of 30HV compare with 100HV.

Table 1. Diameter of indentation compare with maximum depth from load-depth curve.

Test force (mN)	100HV block			30HV block		
	d1(μm)	d2(μm)	Depth(μm)	d1(μm)	d2(μm)	Depth(μm)
5	3.24	3.59	0.50	4.18	4.63	0.90
10	3.49	4.53	1.20	4.80	5.56	1.50
15	3.85	5.83	2.00	6.49	7.83	3.00

Due to non standard using of indenter, testing cycle and force applied; even certified hardness were used as reference material, but we can not compare the load-depth curve directly with load-depth curve that come from standard

machine. Regarding to researching on effect of indenter shape [10], the 60° cone indenter and Berkovich indenter were compare. Their results show 0.25μm maximum depth from load-depth curve of Berkovich indenter and 0.37μm from 60° cone indenter at hardness about 100HV by 10mN test force. For 60° cone micro indenter as conform to standard, it should have tip radius less than 0.3 μm which is very sharp when compare with our stylus tip indenter (2 μm tip radius). This evident has showed that this machine should obtain maximum depth on 100HV at 10mN test force lower than 0.3 μm. But from the result on table 1 show result at 10mN test force on 100HV block has maximum depth at 2 μm, which is five times deeper than commercial machine. We can evaluate the degree of hardness from the comparison with the results of 30HV and 100HV standard blocks although the load-depth curve from our machine is different from the results of standard machine.

5. CONCLUSIONS

The first prototype of micro hardness machine was constructed and described that the simple mechanical structure of parallel leaf spring mechanism and small voice coil actuator can generate force in micro Newton range. This machine can give the best resolution of generated force at 50 μN per step with good linearity, less vibration and less hysteresis up to maximum range 20mN. The micro robot stage carrying can provide the benefit of easy control with higher positioning resolution. In the experimental results, it has been shown the ability of this machine that it can show reasonable hardness result when compare between 30HV and 100HV. On next target is the application on bio-cell stiffness analysis. Due to tiny size of micro force machine, it is possible to set up on micro robot, but this experiment need another depth measuring device that small enough to put on micro robot. Then will get micro robot hardness testing system that small and flexible enough in various application use.

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