行政院國家科學委員會專題研究計畫 成果報告

具有內迴路阻尼調整之可控制接觸力掃描探針顯微系統設計(I)

研究成果報告(精簡版)

計 畫 類 別 ： 個別型
計 畫 編 號 ： NSC 95-2221-E-216-012-
執 行 期 間 ： 95 年 08 月 01 日至 96 年 07 月 31 日
執 行 單 位 ： 中華大學機械工程學系

計 畫 主 持 人 ： 林君明

計畫參與人員： 碩士班研究生-兼任助理：林俊杰
教授：林君明

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中 華 民 國 96 年 08 月 10 日

附件一

行政院國家科學委員會補助專題研究計畫 ■ 成果報告 □期中進度報告

具有內迴路阻尼調整之可控制接觸力掃描探針顯微系統設計(I)

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共同主持人：
計畫參與人員： 林俊杰

成果報告類型(依經費核定清單規定繳交)：■精簡報告　□完整報告

本成果報告包括以下應繳交之附件：
□赴國外出差或研習心得報告一份
□赴大陸地區出差或研習心得報告一份
□出席國際學術會議心得報告及發表之論文各一份
□國際合作研究計畫國外研究報告書一份

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□涉及專利或其他智慧財產權，□一年□二年後可公開查詢

執行單位：中華大學機械工程學系

中 華 民 國 96 年 8 月 10 日

中文摘要

本研究欲完成一套「可控制接觸力之掃描探針顯微系統」。此系統主要元件包括：XYZ 移動平台、力致動器、線性可調式差分變壓器(Linear Variable Differential Transformer，LVDT)、荷重計(Load Cell)、垂直鑽石探針頭、驅動電路、訊號擷取卡，及自行研發的系統操作程式(Operating System Programming)。基本操作原理是先設定探針與待測物的接觸力(如 40 毫克)，而後運用 XYZ 平台，進行平面掃描，配合荷重計，線性可變差分變壓器，類比/數位訊號擷取卡，並利用 PID 控制器補償，將荷重計的訊號做回授與處理，再將誤差訊號，傳到力致動器，做施力誤差補償。本期研究計畫擬將上述系統加以推廣，並採用線性速度感測器(Linear Velocity Transducer, LVT) ，感測垂直探針的上下移動速度作為迴授，以改善內迴路的阻尼及反應速度。經過初步模擬發現效果不錯，的確有改善力致動器磁滯效應及反應速度的功能。

另一些會影響本系統性能的因素是探針頭，線性差分變壓器，及荷重計。以往是使用尖端半徑為 2 μm、張角 60 度的鑽石探頭。而線性差分變壓器的精度為 1μm。荷重計的解析度為 40 毫克。為了使本系統在量測精度上能夠再提高，將另外購置經過雷射加工，尖端半徑為 100 奈米，張角為 10 度的探針頭。所以只要系統後端信號處理技術再提高，如選用靈敏度為 5 毫克的荷重計，及精度更高的線性差分變壓器，即可以獲得更高精度的待測物表面資訊。

為了提高量測的精確度，本研究尚考慮將一面反射鏡，架在探針模組的頂端，將探針模組高度的變化，經由一個槓桿的轉動，轉換成角度的變化。並運用氦氖雷射(He-Ne Laser) ，及四象限感測器(Position Sensitive Detector) ，收集探針頂端反射信號的位移，這樣利用光學放大的原理，可以放大探針的上下移動情況，得到精度更高的資訊。而後利用線性差分變壓器，及四象限感測器所得到的兩種輪廓資訊，各別先進行卡門濾波器(Kalman Filter)處理，其次作多重信號整合(Multi-Sensor Data Fusion)，即可作為最後的量測輸出，其精度會更高。

關鍵詞: 線性速度感測器，線性差分變壓器，荷重計，氦氖雷射，四象限感測器，卡門濾波器，多重信號整合

英文摘要

This research is going to upgrade the previous work of a contact force controlled scanning probe microscopy system design, the main part of this system are as: XYZ-stage, force actuator and driving circuit, Linear Variable Differential Transformer(LVDT), Linear Velocity Transducer(LVT), load cell, diamond probe, data acquisition board, and operating system programming. By using PID controller, the contact-force of the probe is feedback for monitoring the force actuator to meet the desired contact-force between the probe and the object as well as to minimize the hysteresis effect of the force actuator. Finally, the profile of the object surface is displayed on a 3D graph. The accuracy of the system is 1 μm.

This research is going to use Linear Velocity Transducer (LVT) to detect the vertical moving velocity of the stylus probe for the force actuator inner-loop damping and transient behavior control. This improvement has been verified by MATLAB simulation to reduce the hysteresis effect and the transient response of the force actuator.

The other effects that will degrade the performance of measurement accuracy are probe tip, Linear Variable Differential Transformer (LVDT), and load cell. In the previous work, the probe tip is with radius 2 μm and angle 60 degrees. The accuracy of LVDT is 1μm. The measurement resolution of load cell is 40 mg. To improve the system performance of the proposed surface profiler this project is going to purchase the probe tip with radius 100 nm and angle 10 degrees. The resolution of load cell is 5 mg, and the up-graded LVDT as well as the circuit layout artwork.

In addition, to further upgrade the performance of the proposed surface profiler, a reflective mirror is also going to be applied at the top of probe module, which can reflect the beam of a He-Ne laser to a Position Sensitive Detector (PSD) to amplify the displacement of the probe due to the up-and-down movement of sample profile.

Keywords: Linear Velocity Transducer (LVT), Linear Variable Differential Transformer (LVDT), Load Cell, He-Ne Laser, Position Sensitive Detector (PSD), Kalman Filter, Multi-Sensor Data Fusion

前言

由於我國目前正大力推動兩兆雙星產業，所以投入大量資金，購買設備與訓練高科技人才。21 世紀高科技產品之開發趨勢，更是朝向超微小材料結構方向發展。此時亟需正確量測與描述奈米材料物理性質之儀器，如半導體、光電、及硬碟製造技術，不斷推陳出新，有一個共同的特徵：就是對加工物表面的平坦，或輪廓的要求越來越高。例如半導體晶圓在進行金屬化連線製程之前，需要先做平坦化處理（CMP），以確保金屬連線後的可靠度。而硬碟讀取頭也需要在平坦度極高的磁碟片上飛行，進行資料快速的存取。而光電元件表面粗糙度，也是影響影像傳輸品質的重要因素。所以近來工業界對於各類表面輪廓儀的需求，是非常的殷切。值得我國儘速投入人力及設備進行研發。其中掃描探針顯微術(Scanning Probe Microscopy, SPM)，便是一個極具潛力的技術。由於 SPM 已在實驗室中展現出搬移單原子，並製造原子尺寸材料結構的能力，也可在真空、空氣、水溶液等環境下操作，使得掃描探針顯微術，成為奈米科技的發展基礎，並受到全球科技界的重視。但是國內在發展高科技產業的同時，其中最重要的 SPM 等相關檢測設備，須向其他先進國家購買，不但設備價格高昂，維修不易，如果碰到競爭對手干預，則將會遭到設備出口管制問題。所以本研究是建立自製檢測設備的能力與基礎，而以發展接觸式掃描探針顯微系統為出發點。

研究目的

由於可控制接觸力之掃描探針顯微系統，複雜性比前述之 SPM 檢測設備低，環境容忍能力也較高。而檢測的精度可以利用機構的設計，數值處理的手法，以及電路方面的提升，而具有開發的潛力。由計畫主持人前一部份五年內的研究經歷可知，以往本研究已經完成一套精度可達 1μm 的接觸式掃描探針顯微系統，如圖 1。本計劃的目的是將量測的精度，提升一個數量級。

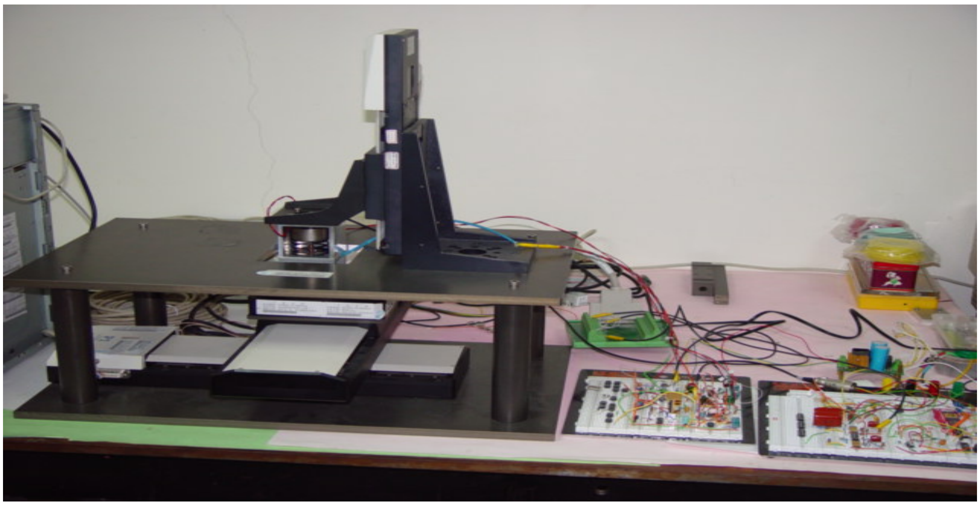


圖 1 可控制接觸力之掃描探針顯微系統

以往研發之系統主要元件包括：XYZ 移動平台、力致動器、線性可調式差分變壓器(Linear Variable Differential Transformer，LVDT)、荷重計(Load Cell)、垂直鑽石探針頭、驅動電路、訊號擷取卡，及自行研發的系統操作程式(Operating System Programming)。基本操作原理是先設定探針與待測物的接觸力(如 40 毫克)，而後運用 XYZ 平台，進行平面掃描，配合荷重計，線性可變差分變壓器，類比/數位訊號擷取卡，並利用 PID 控制器補償，將荷重計的訊號做回授與處理，再將誤差訊號，傳到力致動器，做施力誤差補償。系統硬體架構連結及 MATLAB 模擬方塊，如圖 2 及 3。最後是將擷取到的數位資料，利用軟體程式，以畫面呈現在電腦螢幕上，如圖 4。由此圖可知系統的性能會受到力致動器遲滯效應(Hysteresis Effect)的影響，如圖 5。

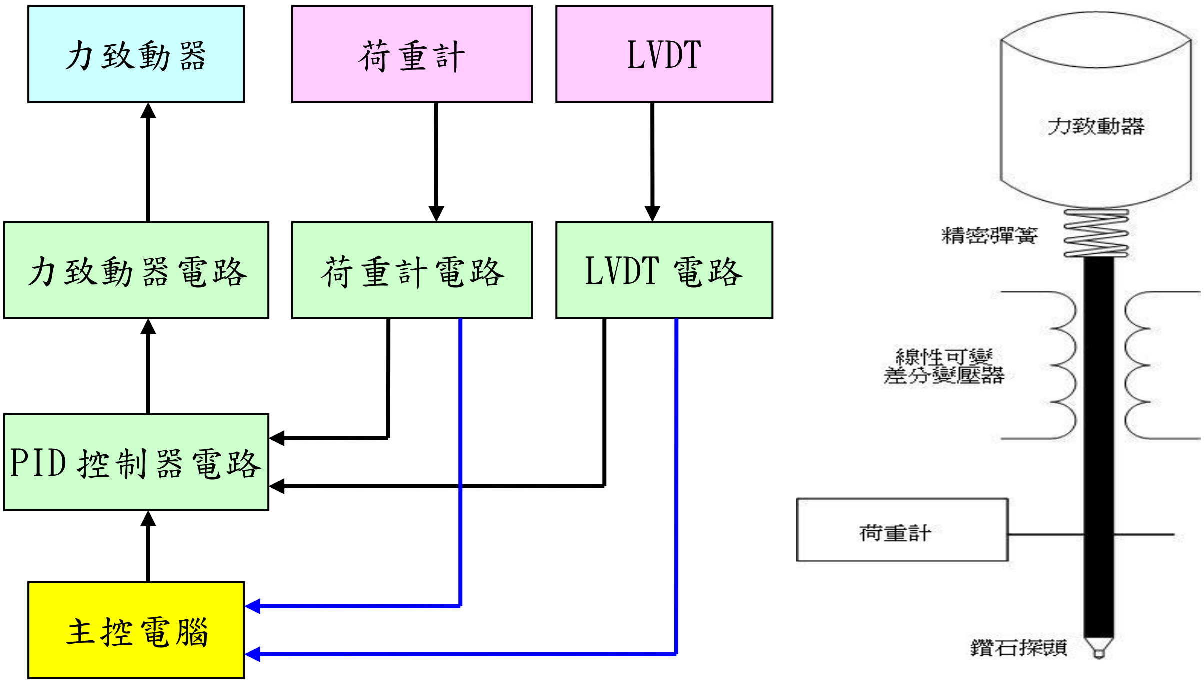


圖 2 可控制接觸力之掃描探針顯微系統(a)架構連結方塊及(b)硬體圖

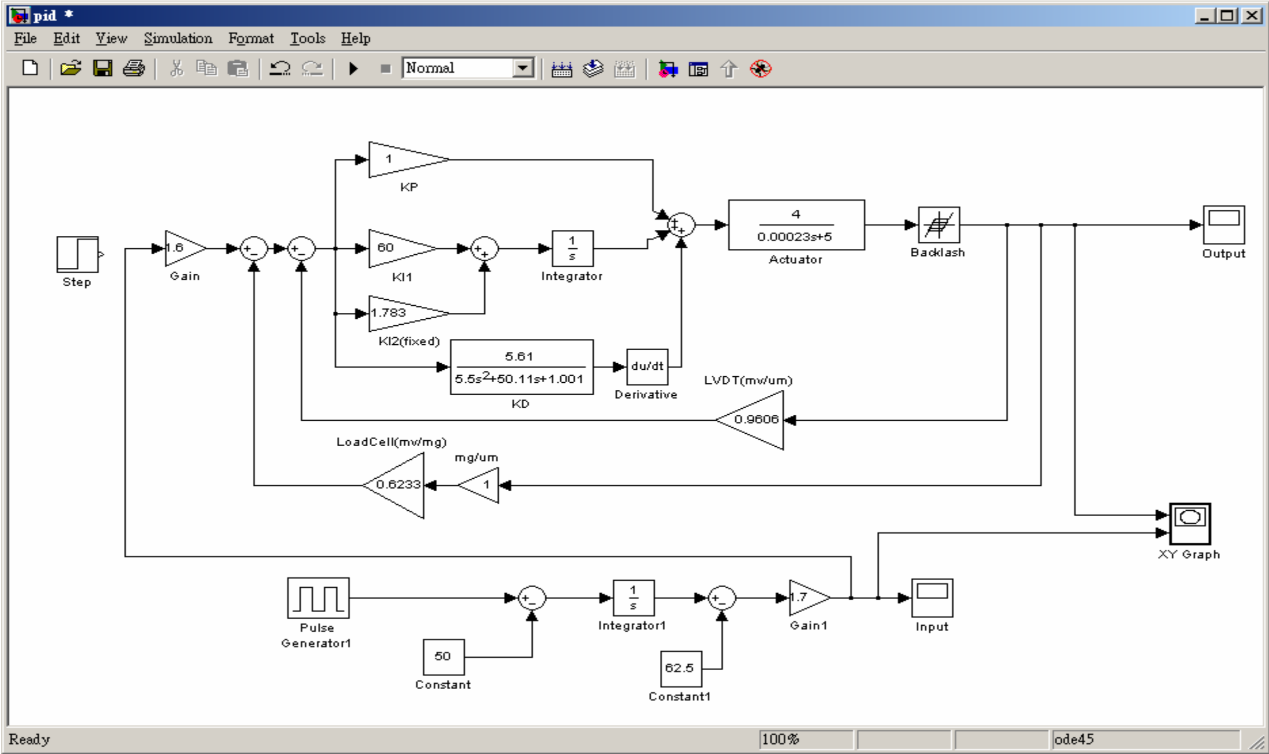


圖 3　MATLAB 系統模擬方塊圖

圖 4 印刷電路板表面量測高低分佈的情形

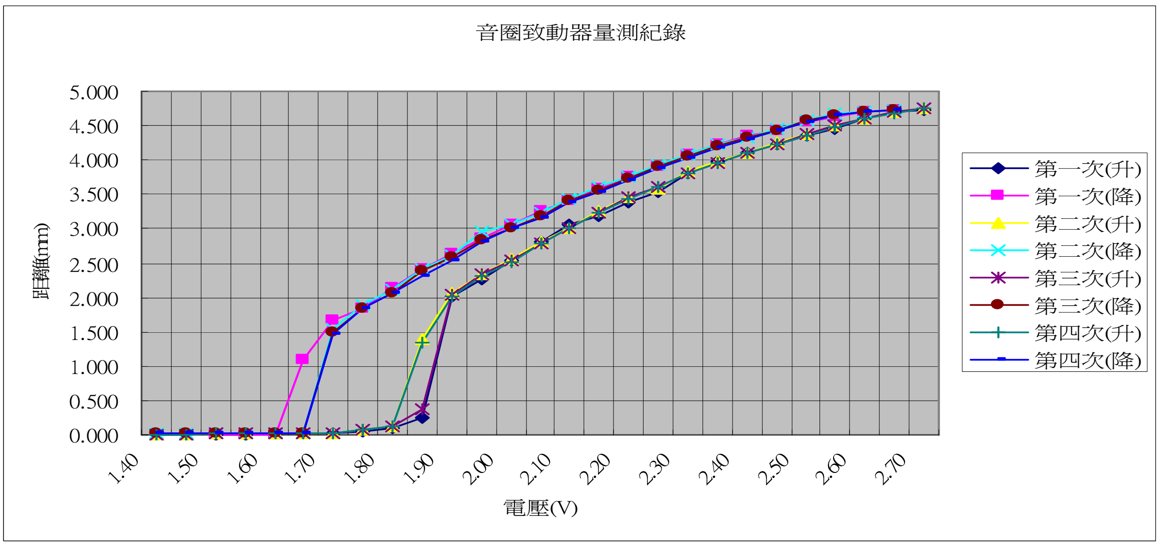


圖 5 力致動器特性(磁滯效應)曲線量測圖

後來解決的方法是在前向迴路中，加入 PID 控制器，雖可降低其影響，但是微分控制器會造成雜訊放大效應，所以後來沒有採用，如圖 7-9 所示是只有在前向迴路中，用到 PI 控制器的力致動器(a)輸入三角波,(b)輸出三角波,及(c)磁滯效應曲線圖，當積分器的增益逐漸增加，超過某一數值時，此種補償方式對於力致動器磁滯效應的改善，趨於一極限。而另一方面，當積分器的增益太高時，系統反應變差，量測結果比較容易震盪而不穩定，為一項缺點。

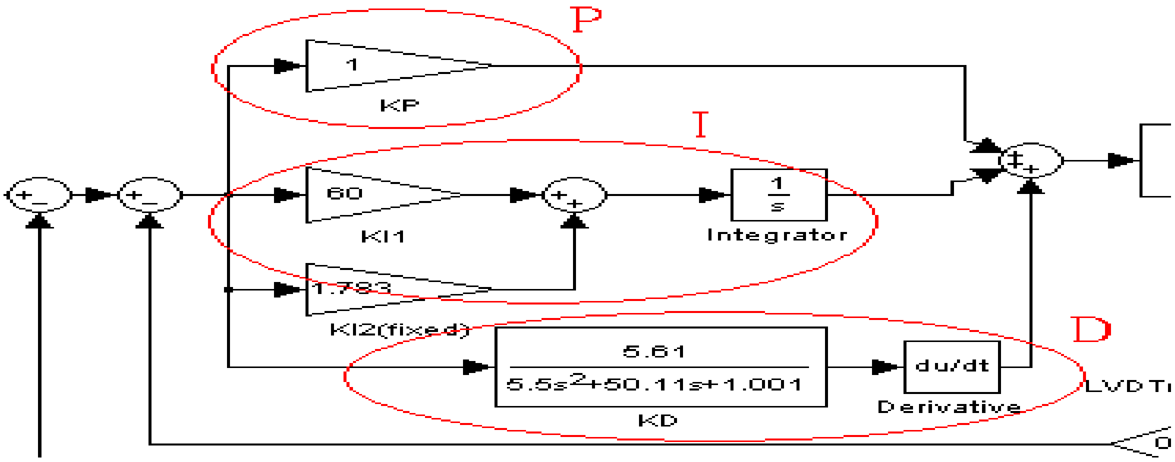


圖 6　PID 控制器方塊圖

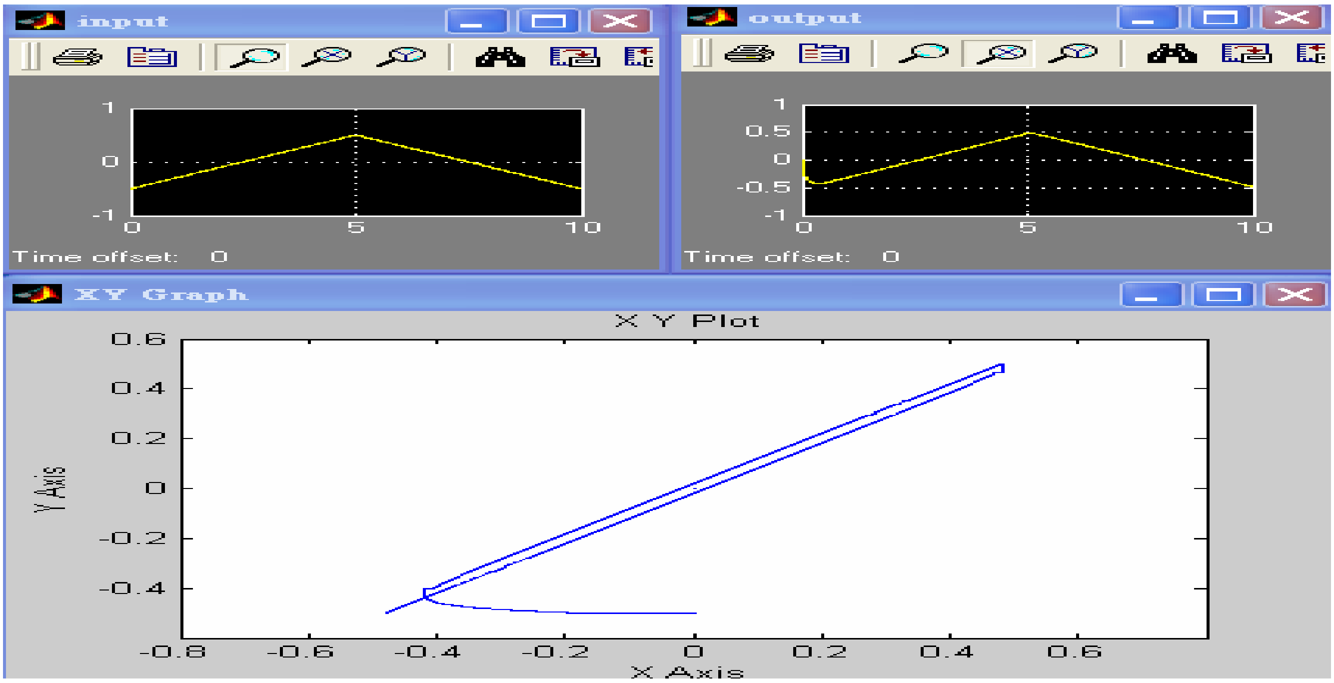


圖 7 P = 0.5，I = 10 之力致動器(a)輸入三角波,(b)輸出三角波,及(c)磁滯效應曲線圖

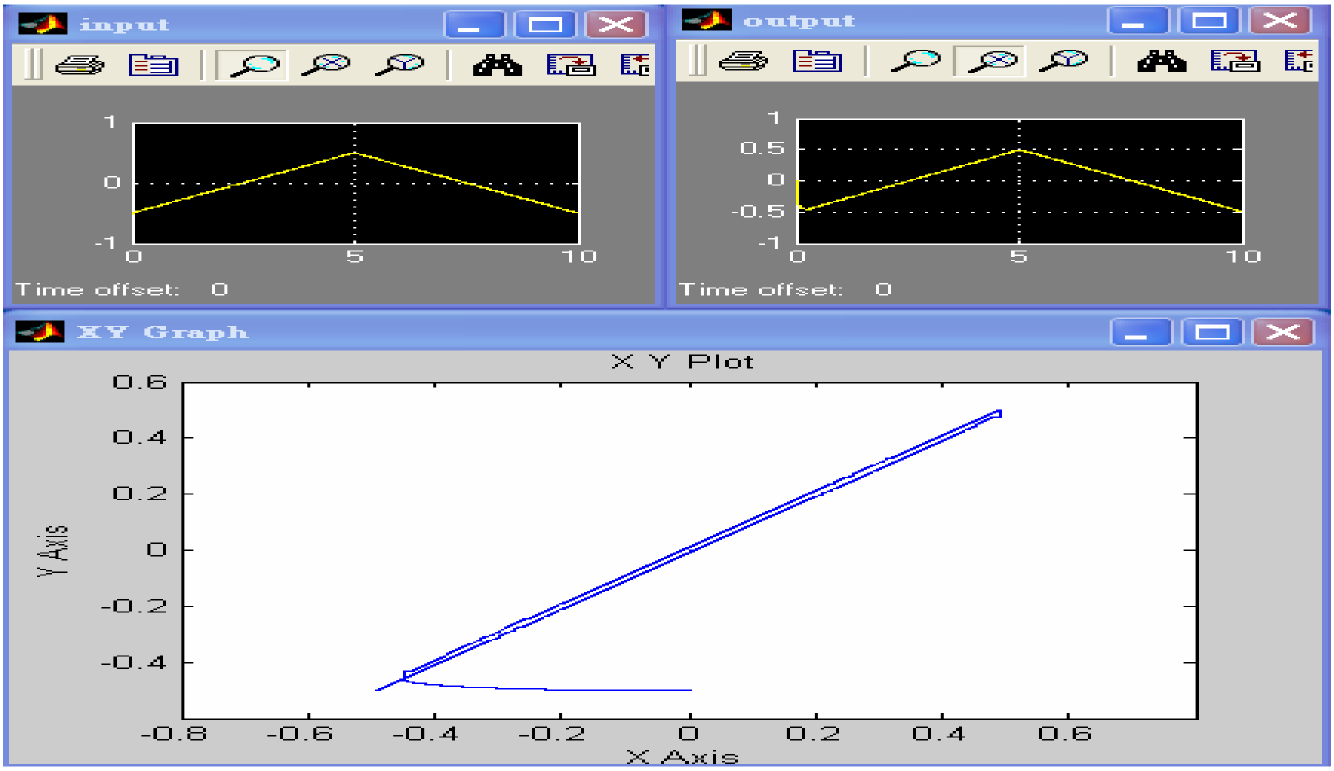


圖 8 P = 0.5，I = 20 之力致動器(a)輸入三角波,(b)輸出三角波,及(c)磁滯效應曲線圖

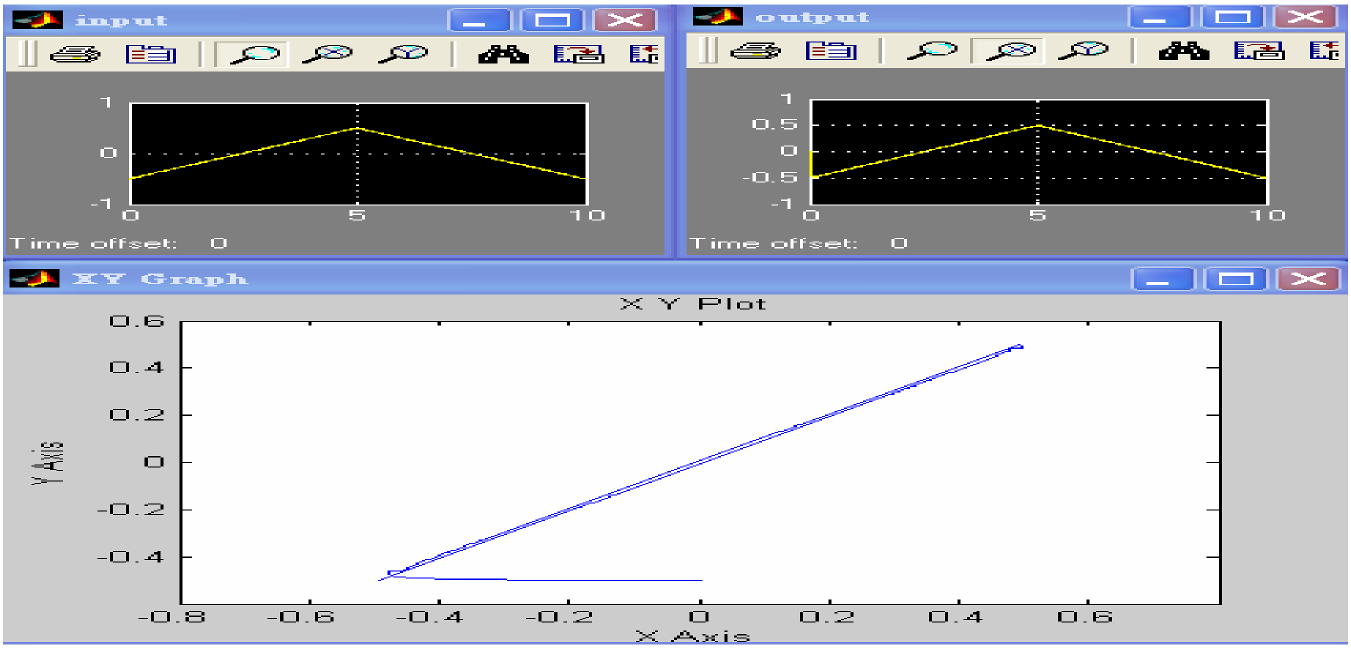


圖 9 P = 0.5，I = 50.5 之力致動器(a)輸入三角波,(b)輸出三角波,及(c)磁滯效應曲線圖

研究方法

本研究計畫擬採用線性速度感測器(Linear Velocity Transducer, LVT) ，感測垂直探針的上下移動速度作為迴授，以改善力致動器內迴路的阻尼，及反應速度(Inner-Loop Damping and Transient Response)，如圖 10。經過模擬發現效果不錯，的確有改善力致動器磁滯效應的功能，如圖 11(內迴路補償器只有 P=1 之結果) ，及圖 12(內迴路補償器只有 P=1, I=200 之結果) 。比較圖 12 及圖 9，可見這種內迴路採用速度感測器作為迴授，不僅可以改善內迴路的阻尼及反應速度，也可以改善力致動器磁滯效應。

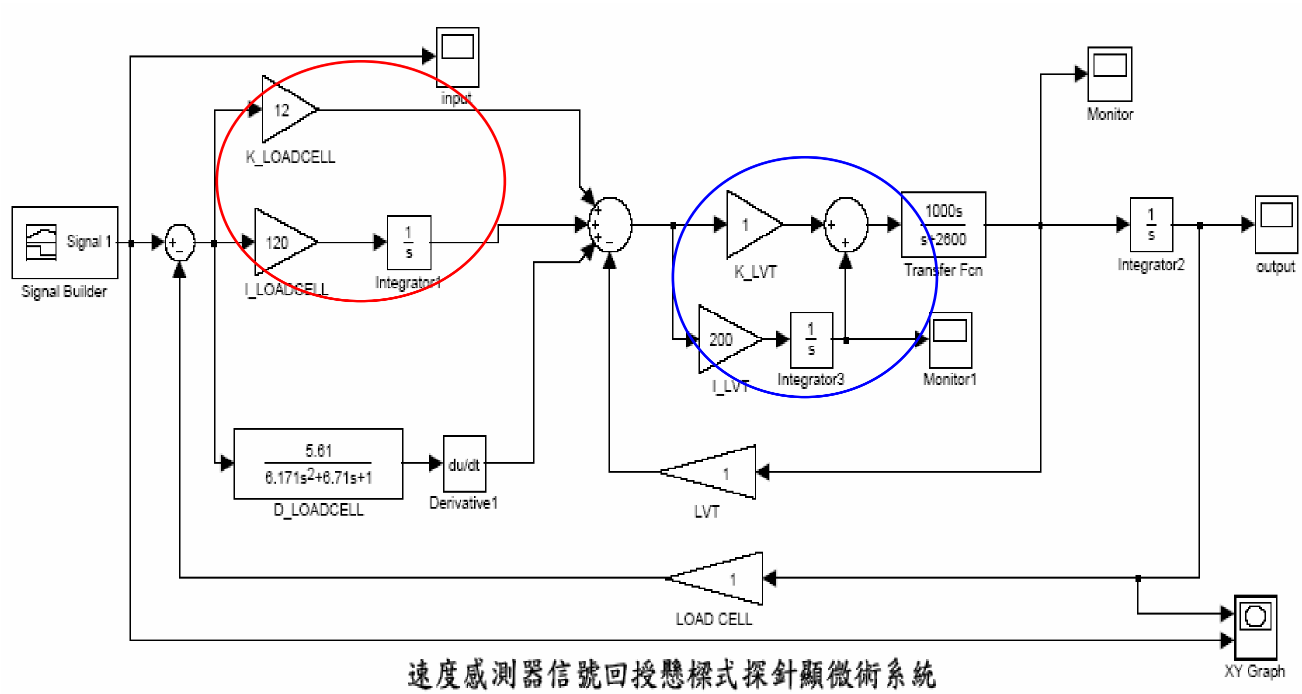


圖 10 採用線性速度感測器(LVT)作為回授，改善內迴路的阻尼及反應速度之系統方塊圖

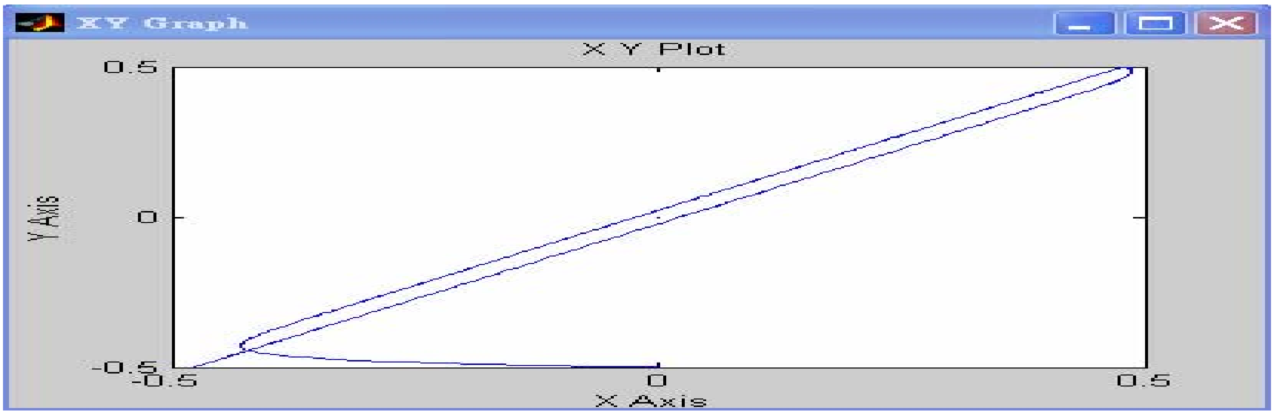


圖 11 內迴路補償器只有 P=1 之力致動器磁滯效應曲線圖

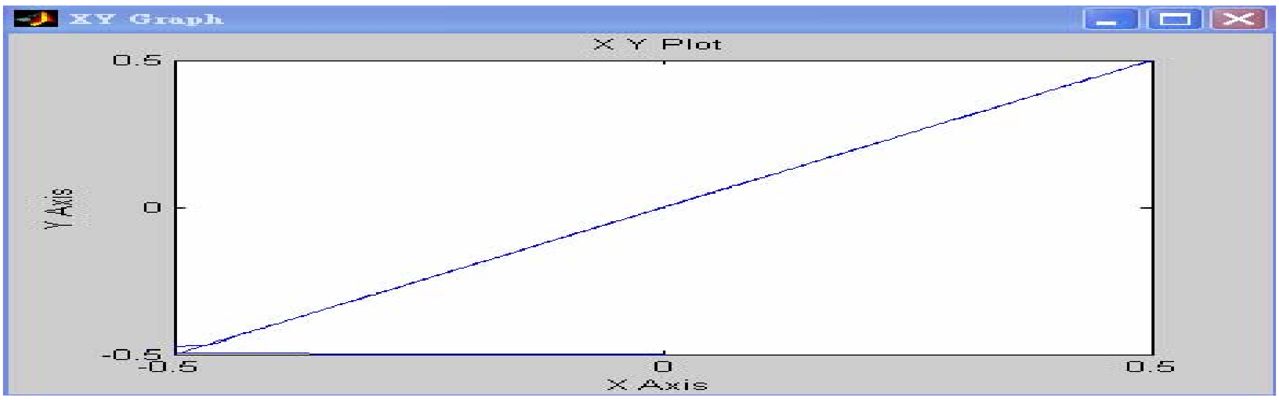


圖 12 內迴路補償器只有 P=1, I=200 之力致動器磁滯效應曲線圖

經過以上的模擬分析，我們確認此種研究構想的可行性之後，即可進行系統硬體的採購，如線性速度感測器(LVT) ，與補償器電路設計製作，如下列圖 13 及 14。

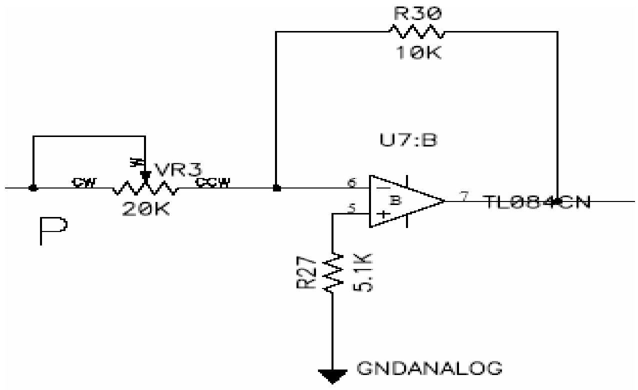
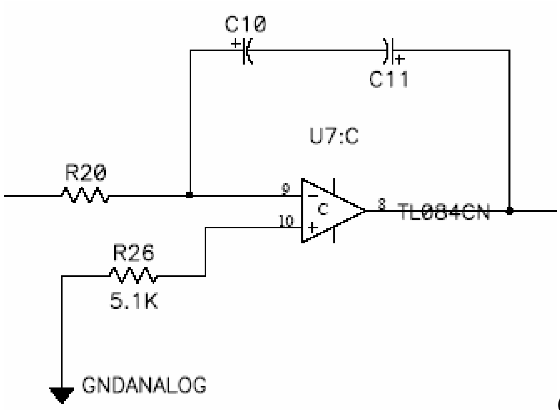


圖 13　PI 控制的 P 參數控制與實際電路



$$G_C(s) = -\frac{1/R_{20}C}{S}$$

圖 14　PI 控制的積分參數控制與實際電路

結果與討論

另一些會影響本系統性能的因素是探針頭，線性差分變壓器(LVDT)，及荷重計(Load Cell)。以往是使用尖端半徑為 2 μm、張角 60 度的鑽石探頭，如圖 15。而線性差分變壓器的精度為 1μm，如圖 16。荷重計的解析度為 40 毫克，如圖 17。為了使本系統在量測精度上能夠再提高，將另外購置經過雷射加工，尖端半徑為 100 奈米，張角為 10 度的探針頭。所以只要系統後端信號處理技術再提高，如選用靈敏度為 5 毫克的荷重計，及精度更高的線性差分變壓器，即可以獲得更高精度的待測物表面資訊。

而為了要測試本系統的精度，本計畫擬自行製作標準塊規(Gauge Meter)。其方法就是先製作光罩(Photo Mask)，上面有不同的幾何圖案，各圖案的厚度輪廓又有不同的分佈，而後運用國科會晶片製作中心(Chip Implementation Center, CIC)，下線之台積電半導體及微機電製程，運用 P 型-硼(P-Type Boron)雜質擴散，及其對 KOH 有蝕刻阻擋之作用，即可精確的控制各圖案的厚度，將此標準塊規製作出來，以供自製之掃描探針系統性能測試之用。

圖 15 鑽石探針頭及聯結組件

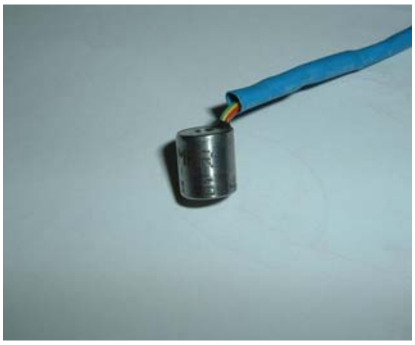


圖 16 線性差分變壓器

圖 17 荷重計

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成果自評

(1)進行荷重計(Load Cell) ，線性差分變壓器(LVDT) ，線性速度感測器(LVT) ，及四象限感測器(PSD)採購，及電源電壓、溫度之穩定性分析與偏差量補償(Bias Compensation)技術。

(2)線性速度感測器內控制迴路放大補償器參數模擬，電路設計，及機電系統整合機械結構設計，及硬體製作。

(3)自行製作標準塊規，進行荷重計及線性差分變壓器(LVDT) ，線性速度感測器(LVT)，與資料擷取系統等，機電系統整合，資料之擷取及靈敏度性能調校。

(4)於 2007 年自動控制研討會發表一篇文章題目是:

Scanning Probe Microscope System Design with Linear Velocity Transducer for Feedback Compensation

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Scanning Probe Microscope System Design with Linear Velocity Transducer for Feedback Compensation

Jium-Ming LIN
School of Mechanical Engineering and Astronautics, Chung-Hua University
Hsin-Chu, Taiwan, ROC
e-mail: jmlin@chu.edu.tw

Chun-Chieh LIN
School of Mechanical Engineering and Astronautics, Chung-Hua University
Hsin-Chu, Taiwan, ROC
e-mail: m09308037@chu.edu.tw

***Abstract*—This research is to use Linear Velocity Transducer (LVT) to detect the vertical velocity of the stylus probe for the inner-loop damping and transient control of a force actuator. This improvement has been verified by MATLAB simulation and practical implementation of a surface profiler to reduce the hysteresis effect of the force actuator.**

***Keywords* —LVT, LVDT, Load cell, Surface profiler.**

I. INTRODUCTION

The Scanning Probe Microscopy (SPM) has been developed rapidly in the last two decade [1]. Its usage is very extensive, for example, the measurements of physical distribution and material property such as surface profile, roughness, static charge, magnetic dipole, friction, elasticity, and thermal conductivity. As shown in Fig.1 of past research [2], a balance with stylus probe, force actuator, LVDT (Linear Variable Differential Transformer), load cell, personal computer, and XYZ- stages was integrated into a contact-force-controlled Scanning Probe Microscope (SPM) system, such that the surface of the sample would not be destroyed by the contact force produced by the stylus probe. This research is to use Linear Velocity Transducer (LVT) in Fig. 2 to detect the vertical velocity of the stylus probe for the inner-loop damping and transient control of the force actuator.

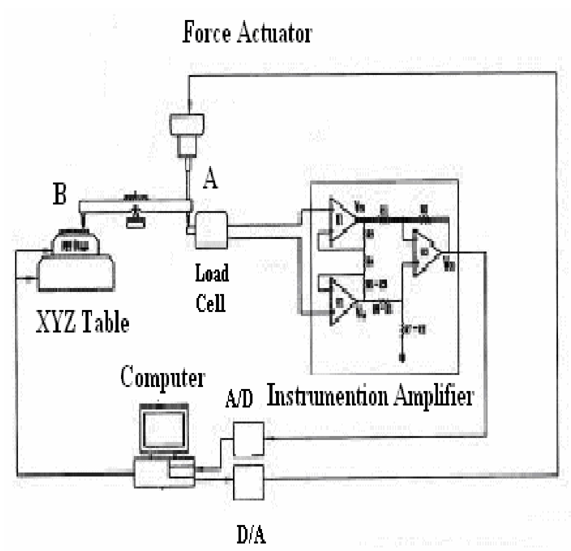

Fig.1. The contact force-controlled SPM system.

The stylus probe is shown in Fig.3, the voice coil was applied as a force actuator (Fig. 4a), which was integrated with LVT and LVDT (Fig. 4b) to measure the probe vertical displacement and velocity. The load cell in Fig. 5a was used to detect the contact force between the probe and sample to be tested. A leaf spring in Fig. 5b was applied to integrate the load cell with voice coil, LVT and LVDT module as shown in Figs. 5c and 5d.

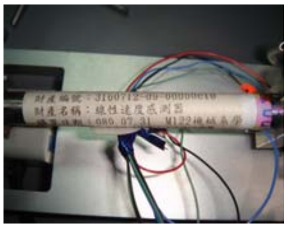

Fig. 2. The LVT.

Fig. 3. The stylus probe.

Fig.4a. The voice coil.

Fig. 4b. The LVDT.

Fig. 5a.The load cell.

Fig. 5b.The leaf spring.

In addition to the XYZ-stages a piezo-stage in Fig. 6 was also put on the Z-stage to improve the measurement accuracy. The personal computer was the central control unit for the whole operation, such as setting the contact force between the probe and the sample, taking the contact force information from the load cell, as well as driving the force actuator for the balance-arm initial leveling. Thus it is an automatic SPM system.This improvement has been verified by MATLAB simulation and practical implementation of a surface profiler to reduce the hysteresis effect of the force actuator.

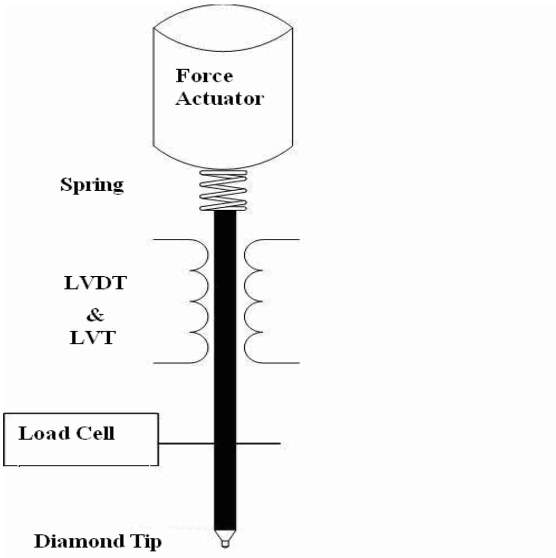

Fig. 5c. The installation structure of load cell, voice coil LVT and LVDT.

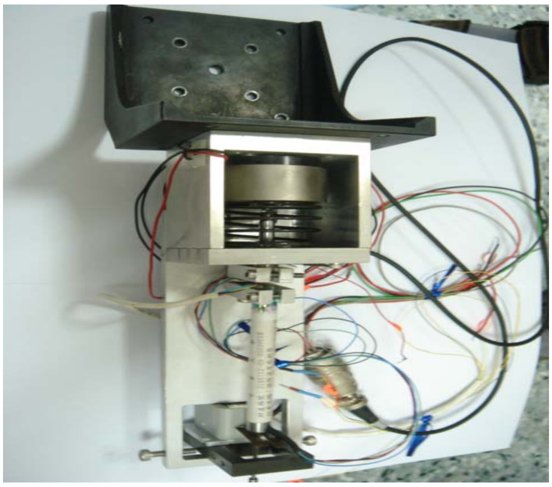

Fig. 5d. Integration of voice coil, LVT & LVDT.

Fig. 6. The piezo-stage and the sample holder.

II. Principle of System Design

The structure of the system is shown in Fig.1. The major part is the balance. The stylus probe is on the left side, while the force actuator and the load cell are on the upper and the lower parts of the right side, respectively. The force actuator is consisted of a coil and a spring as in Fig. 7a, when a voltage is applied across the coil, then there is current in the coil, and a force is generated to compress the spring and make a vertical displacement as shown in Fig. 7b.

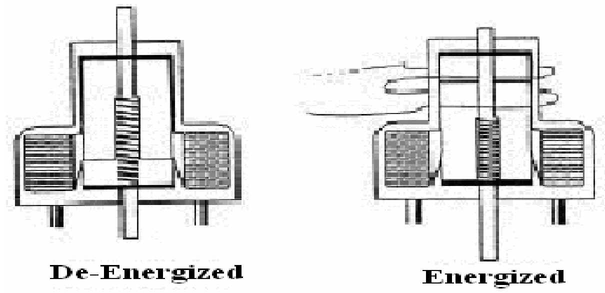

Fig.7a. Force actuator de-energized. Fig.7b. Force actuator energized.

The relationship of the applied voltage and the displacement is shown in Fig. 8. In order to reduce the hysteresis-effect of the force actuator in Fig. 8, a PI compensator in the forward path as well as a LVT measuring the vertical velocity as the feedback path of the force actuator, were applied in this research as shown in Fig. 9. A saw tooth-shaped voltage (with peak value =100 mV) as shown in Fig.10, which stands for the displacement command of the force actuator as well as the probe, is applied to the input of the compensated force actuator.

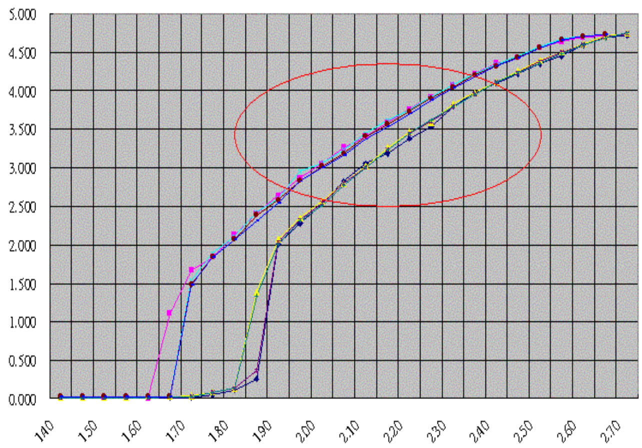

Fig. 8. The relationship of the applied voltage and the displacement of force actuator.

If the gains of the compensator are set as P=1, then the output of LVDT is shown in Fig. 11 by MATLAB simulation. One can see the hysteresis effect still exists as shown in Fig. 12 with output and input on the x and y axes, respectively. After a little while of trial-and-error one has a very good result with P=1 and I=200, respectively, e.g. the output of LVDT is shown in Fig. 13, and the hysteresis effect is almost disappeared as shown in Fig. 14. Finally, the simulation block diagram of the whole system is shown in Fig.9, in which the desired contact force between the probe and the sample is set as the input command to the system, and a load cell is used as the outer feedback loop sensor.

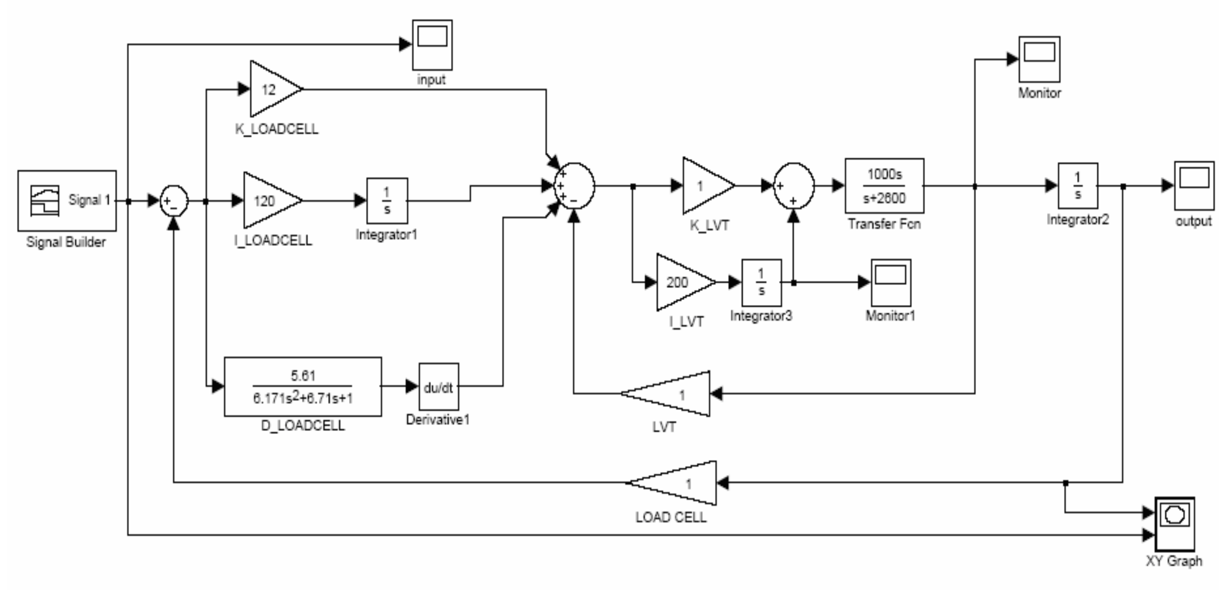

Fig. 9. The design with a PI compensator and a LVT respectively in the forward and feedback paths of force actuator.

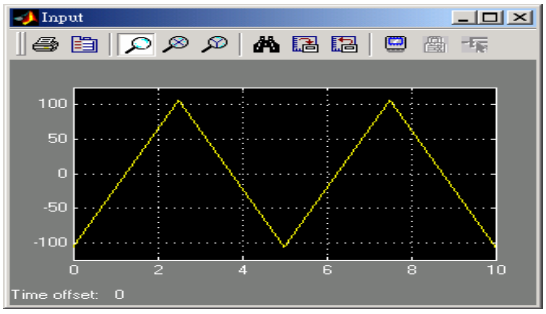

Fig. 10. A saw tooth shaped voltage (displacement command) is applied to the input of the compensated force actuator.

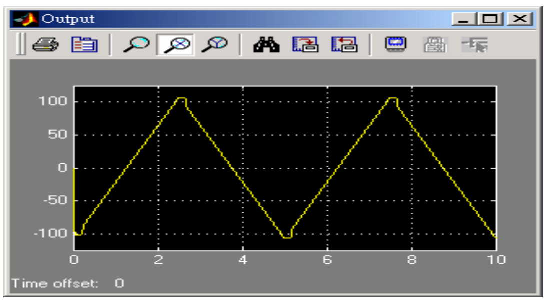

Fig. 11. Output of LVDT shows the hysteresis effect still exists with P=1.

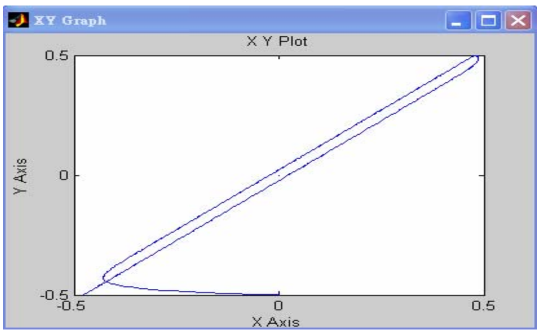

Fig. 12. Hysteresis effect still exists with P=1.

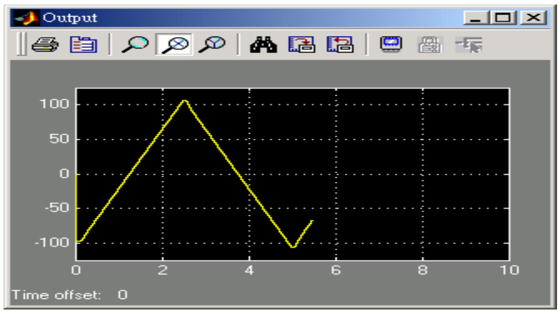

Fig. 13. Output of LVDT shows the hysteresis effect is almost disappeared with P=1 and I=200.

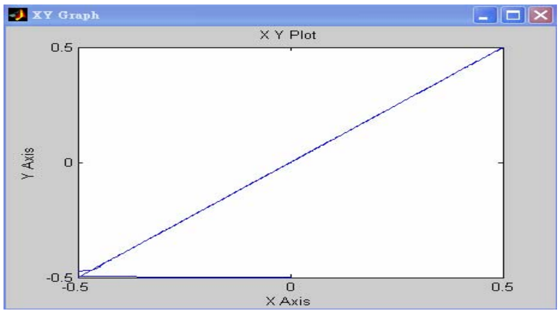

Fig. 14. Hysteresis effect is almost disappeared with P=1 and I=200.

III. Test Results and Discussions

The first step of test is initial levelling of the balance lever arm, which is achieved by adjusting the current through the coil of force actuator. Since the lever arm weight at the stylus probe (contact with the sample) side is heavier than the other side (contact with actuator) intentionally, thus the force actuator should push down to make the balance lever arm even. The contact point of the lever arm on the load cell is installed right at the calibrated-levelling height. This adjustment process stops when the value of load cell output increases from 0 mg to 40 mg as shown in Fig. 15. This value for the weight discrimination can be lowered if the circuit routing condition is better, thus the noise amplitude at the load cell output can be reduced.

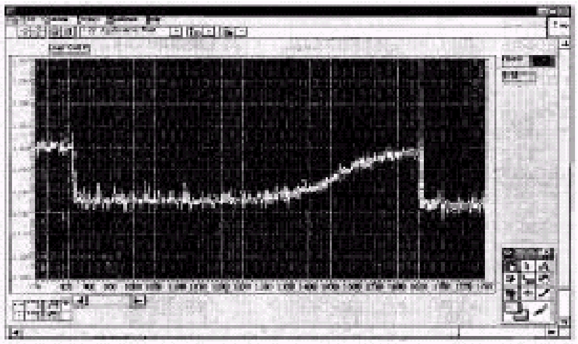

Fig. 15. Output voltage of the load cell is increased for the contact force changing from 0 mg to 40 mg.

The next step is to load the sample on the holder which is fixed on the piezo-stage as well as XYZ-stages, and then setting the XY-stages (the resolution is 34 nm in either axis) to make the first sampled point just right under the tip of the stylus probe, then raising the piezo-stage upward until the sampled point touching with the probe. The value of the probe contact force on the sample can be obtained by the load cell. In order to make sure that the probe contacts with the sample while not destroy it, the maximum contact force is limited to 100 mg, i.e., if the magnitude of contact force is smaller than 100 mg, then moving the piezo-stage upward by one step (the resolution is 10 nm), otherwise, stop. Then by scanning the XY-stages in either x- or y-axis, and finally, the surface profile of the sample can be obtained as shown in Fig. 16 from LVDT. If one should like to see the top view, the result is shown in Fig. 17.

IV. Conclusions

This paper integrates the mechatronics such as: a balance with stylus probe, force actuator, LVT, LVDT, load cell, personal computer, as well as XYZ-stages into a contact-force-controlled SPM system, such that the surface of the sample would not be destroyed by the contact force produced by the stylus probe. This research is to use Linear Velocity Transducer (LVT) to detect the vertical velocity of the stylus probe for the inner-loop damping and transient control of a force actuator. This improvement has been verified by MATLAB simulation and practical implementation of a surface profiler to reduce the hysteresis effect of the force actuator. Finally, the profile of the object surface is displayed on a 3D graph.

Acknowledgment(s)

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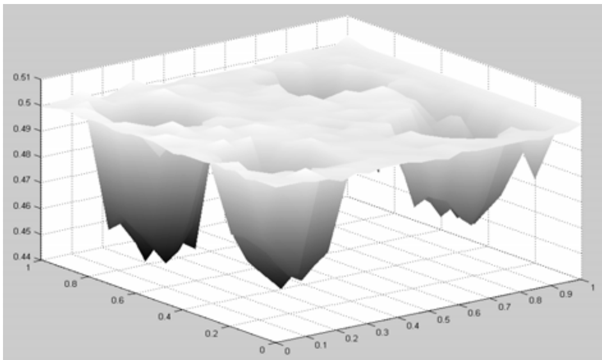

Fig. 16. The surface profile of the sample.

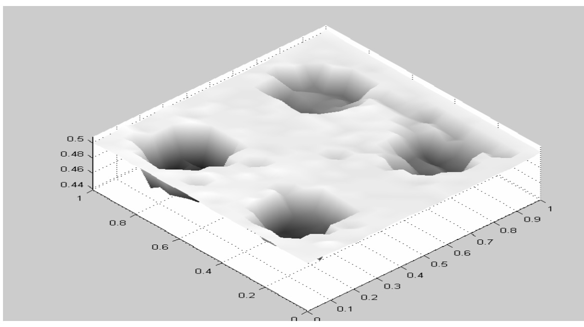

Fig. 17. The top view of the sample.