Eliminating Hysteresis Effect of Force Actuator in a SPM

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Abstract: - This research is to use fuzzy controller to eliminate hysteresis effect of a force actuator for a Scanning Probe Microscope (SPM). This improvement has been verified by MATLAB simulation and practical implementation to reduce the hysteresis effect of the force actuator. Comparisons with two previous designs with and without Linear Velocity Transducer (LVT) for inner-loop feedback compensation are also made. Thus the new system design is cheaper and valuable.

Key-Words: - SPM, LVT, LVDT, Fuzzy controller, PI compensator, Force actuator, Hysteresis effect

1 Introduction

The SPMs have been developed rapidly in last three decade [1-10]. Their usages are very extensive, e. g. the measurements of physical distribution and material property such as surface profile, roughness, static charge, magnetic dipole, friction, elasticity, and thermal conductivity. As the block diagrams in Fig.1 of previous researches [11-12], a balance with stylus probe, force actuator (Fig.2), LVDT (Fig.3), load cell (Fig.4), personal computer, and XYZ-stages were integrated into a contact-force-controlled SPM, such that the sample surface would not be destroyed by the contact force produced by stylus probe. The block diagrams of the control system design with and without LVT for inner-loop feedback [11-12] are shown in Figs.5 and 6, respectively.

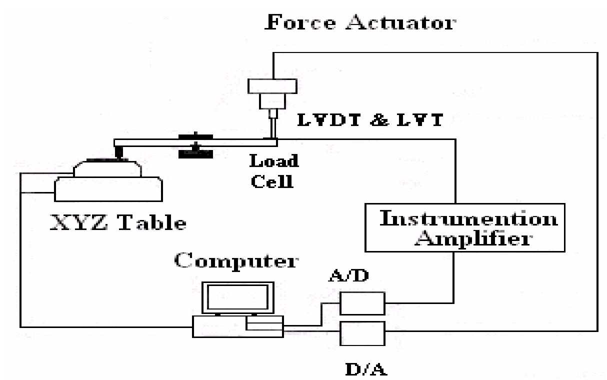


Fig. 1 The system setup of a SPM.

To eliminate hysteresis effect of the force actuator this research in Fig.7 applied an intelligent fuzzy controller [15-18] and without using LVT for inner-loop feedback system design. This improvement has been verified by MATLAB simulation and practical implementation of a surface profiler. Comparisons with two previous designs with and without LVT for inner-loop feedback are also made. Thus the cost of the new system is cheaper, and the concept is also valuable.

The organization of this paper is as follows: the first section is introduction. The second and the third ones are for the review of previous researches and the proposed fuzzy controller design. The test results and discussions are given in Section 4. The last part is the conclusion.

Fig. 2 Voice coil as the force actuator.

Fig. 3 LVDT.

Fig. 4 Load cell.

2 Review of Previous System Design

The force actuator is consisted of a coil and a spring. As in Fig.8 (a) the rod returns to the initial place when the force actuator de-energized. However, if a voltage is applied across the coil, then there is current in the coil, a force is generated to compress the spring and make the rod pull down as in Fig.8 (b). The relationship of the actuator applied voltage and displacement is shown in Fig.9.

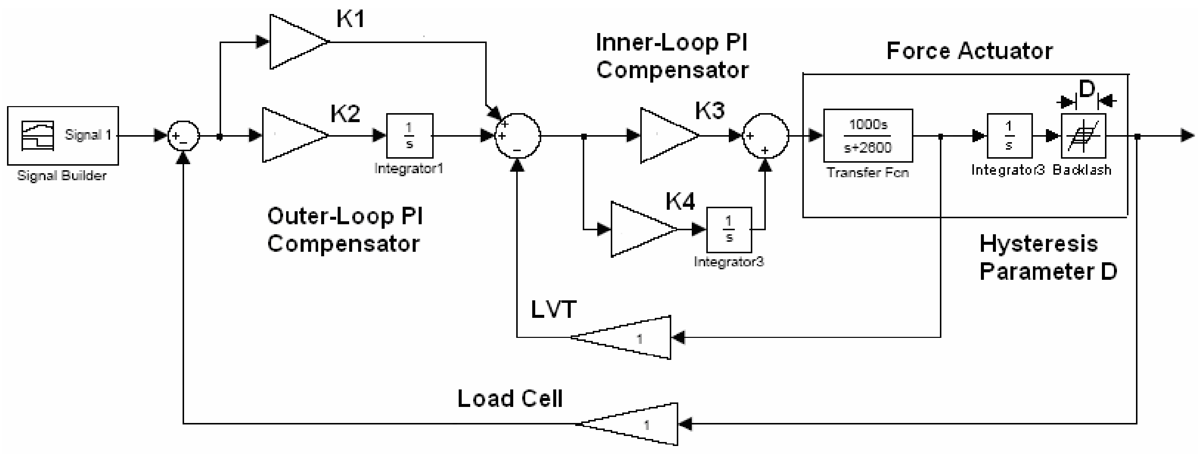


Fig.5 Block diagram of SPM with LVT for inner-loop feedback in the previous research [11].

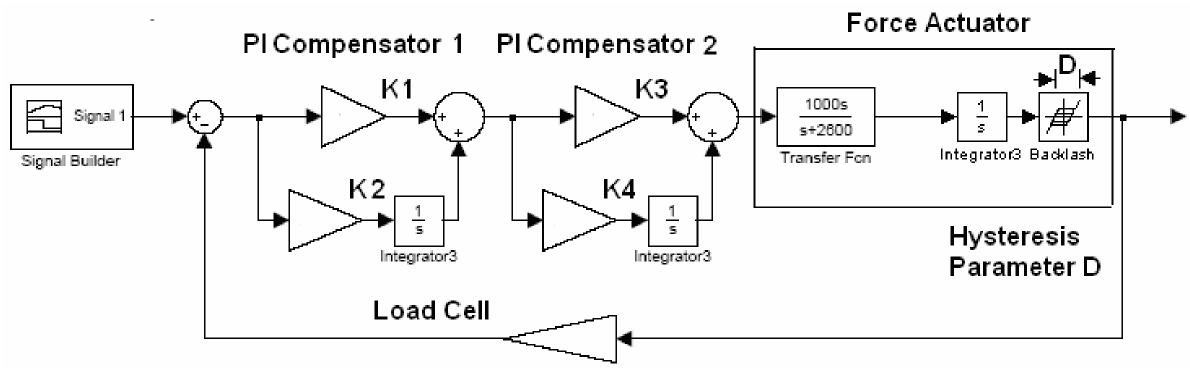


Fig.6 block diagram of SPM without LVT for inner-loop feedback in the previous research [12]

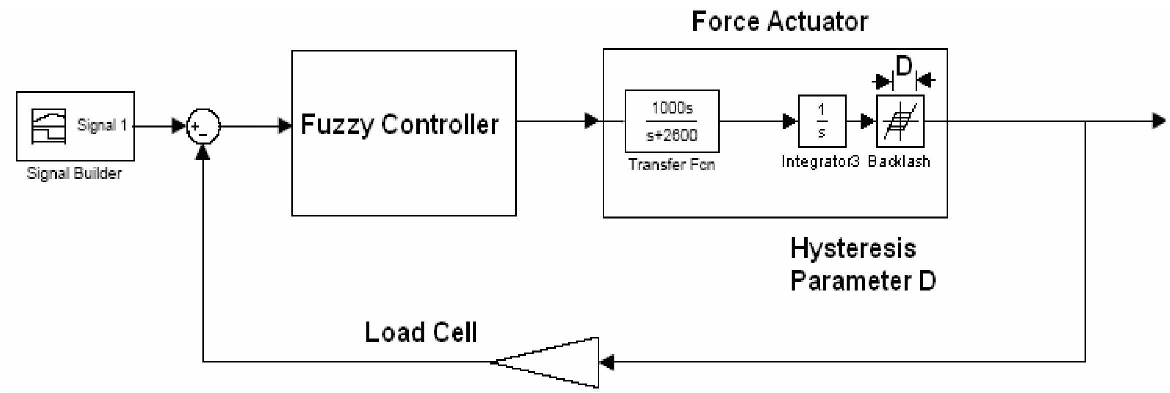


Fig.7 Block diagram of SPM with an intelligent fuzzy controller and without LVT in this research.

To reduce the hysteresis-effect of the force actuator in Fig.9, this research is to use only an intelligent fuzzy controller. The newly system model is shown in Fig.7. Table 1 listed PI compensators for inner and outer loops design (steady state errors are equal to zero for inner and outer loops) results in Fig.5. In addition, the corresponding gain margins, phase margins of the inner (GM1, PM1) and outer (GM2, PM2) loops as well as the phase cross-over frequency ω_c are included. Figs.10-13 are the Bode plots of cases 1, 2, 5 and 6, respectively. The outputs of LVDT for saw tooth shaped input (as in Fig.14) are shown from Figs.15 to 18 for comparison (with hysteresis effect parameter D be 0.3). One can see that the larger the outer-loop phase margin, the lower the hysteresis effect, but all the hysteresis effects are still very dominant. The reason is that ω_c are very large for these cases, and then the time and phase delays produced by the hysteresis effect would be increased. Thus the stability can even be degraded by adding the hysteresis effect to push the resulted phase margins approaching zero.

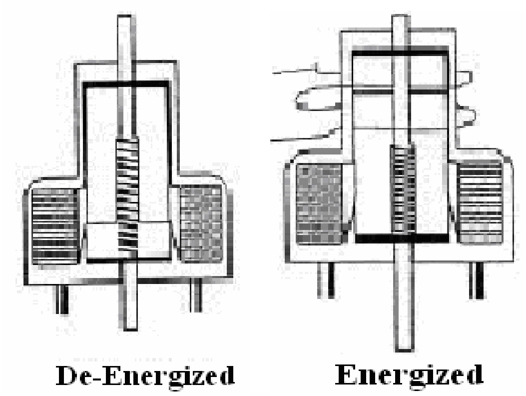


Fig.8 Operation states of actuator.

Table 1 Previous design results of the system defined in Fig 1.

Case	K1	K2	K3	K4	GM1	PM1 (Deg)	GM2	PM2 (Deg)	ω_c (rad/sec)
1	12	120	1	200	∞	73	∞	85	9840
2	10	100	0.8	180	∞	75	∞	70	7500
3	15	100	1.5	200	∞	65	∞	88	20000
4	20	150	2	150	∞	63	∞	89.5	40000
5	8	80	0.5	300	∞	85	∞	60	30000
6	18	200	1.3	220	∞	70	∞	90	30000

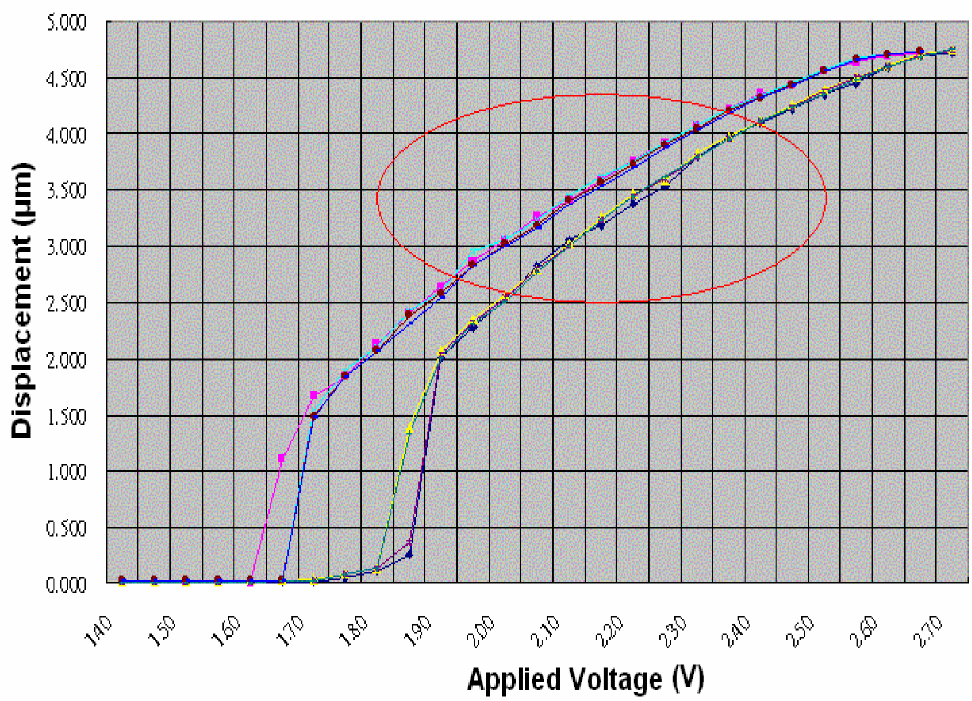


Fig.9 Relationship of actuator applied voltage vs. displacement.

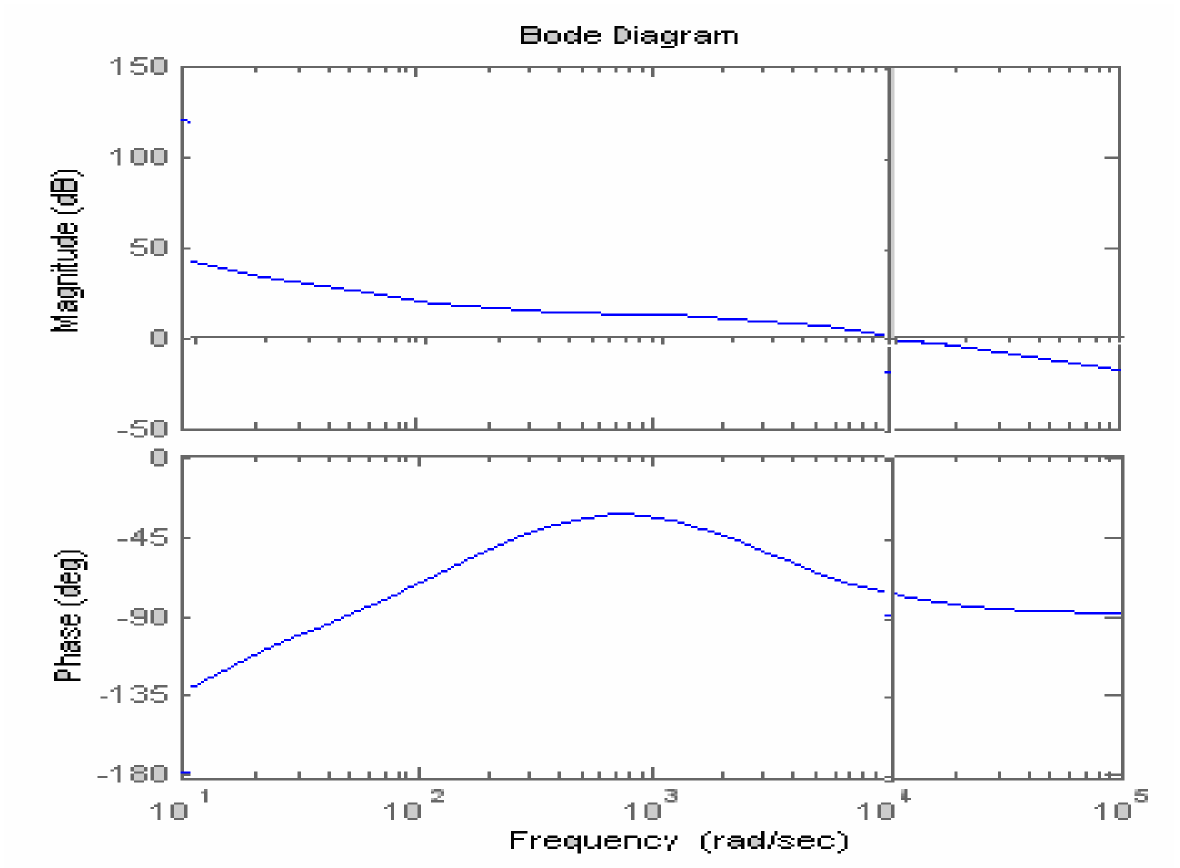


Fig.10 Previous Bode plot of case 1 in Fig. 1.

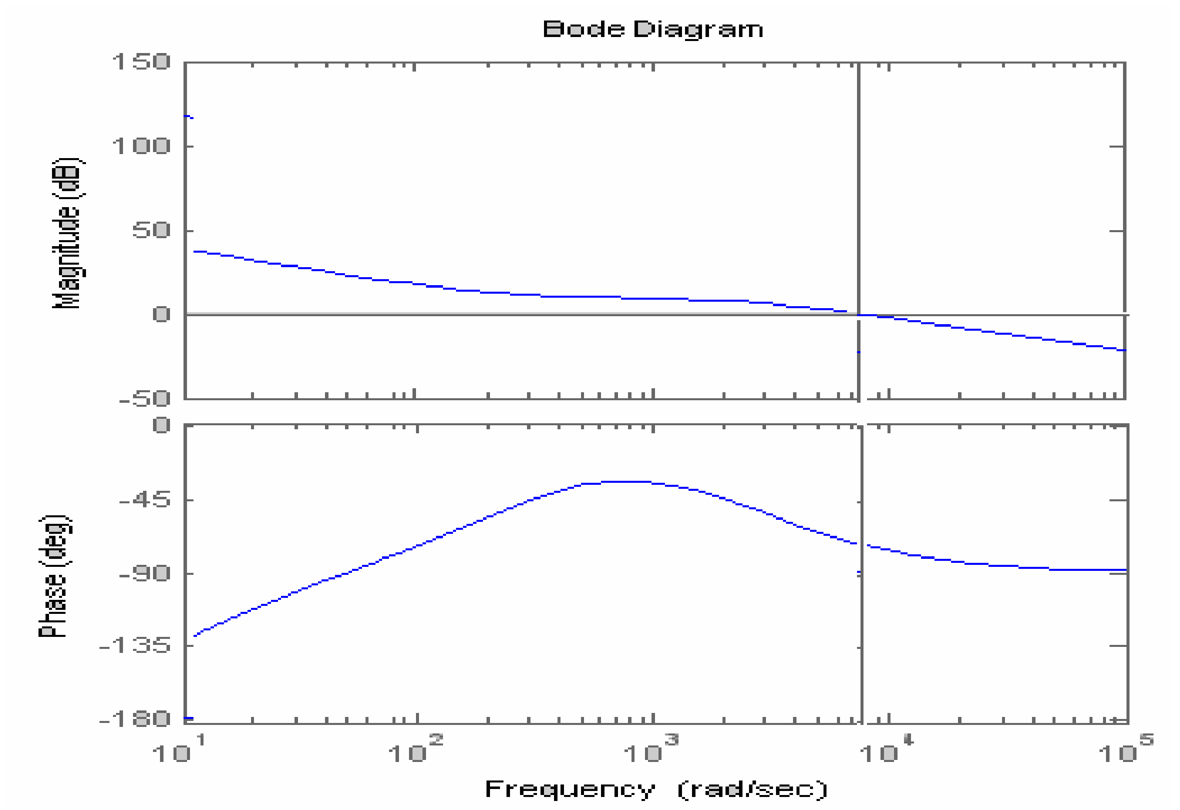


Fig.11 Previous Bode plot of case 2 in Fig. 1.

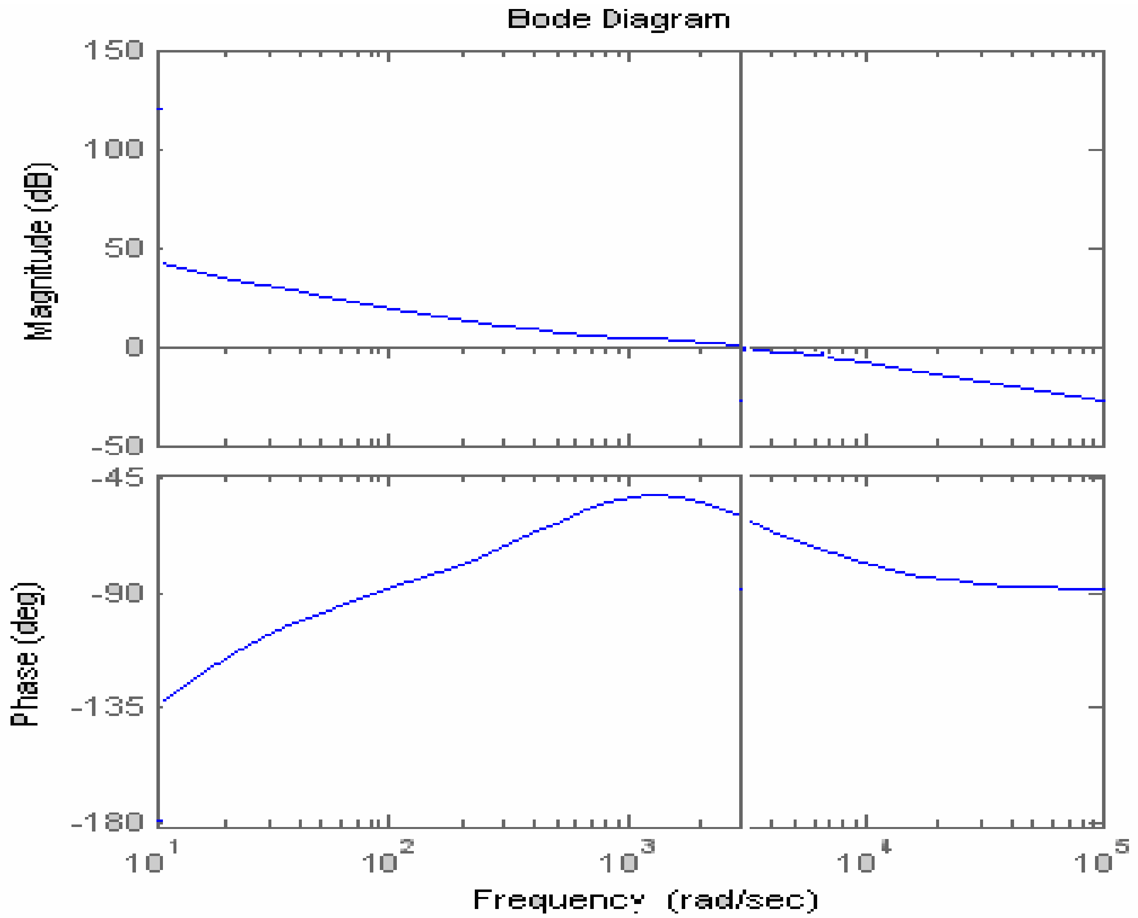


Fig.12 Previous Bode plot of case 5 in Fig. 1.

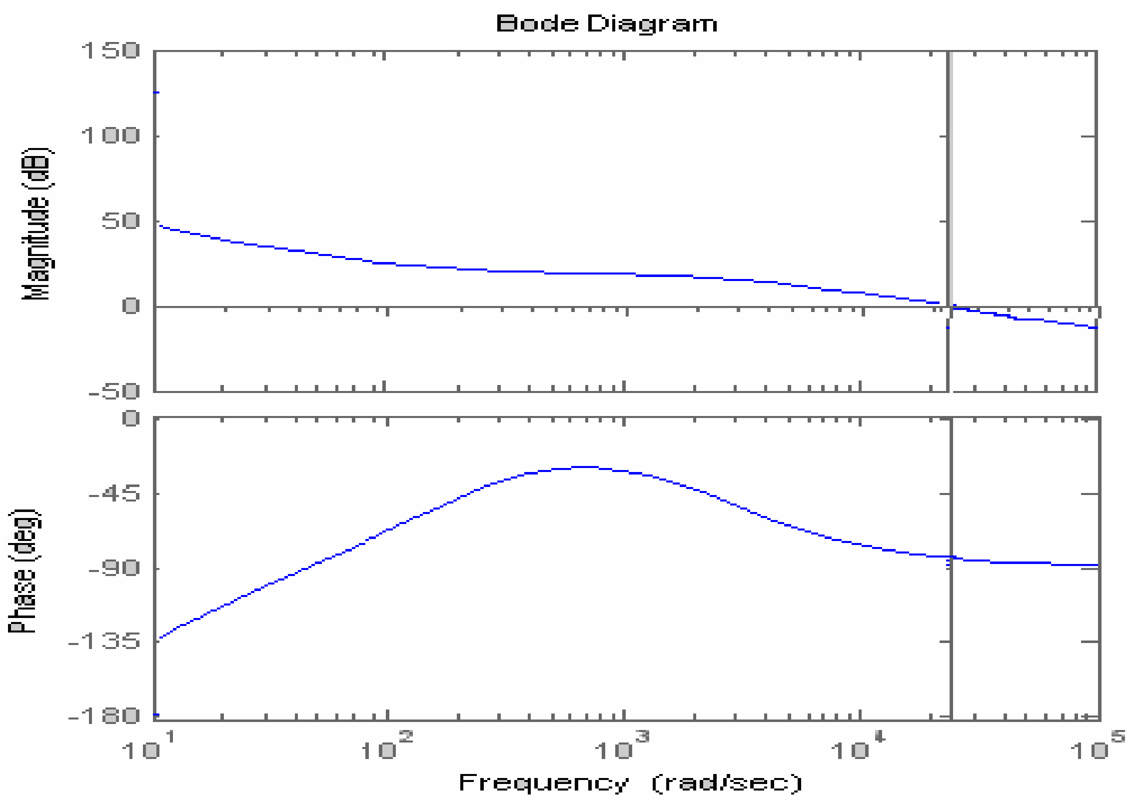


Fig.13 Previous Bode plot of case 6 in Fig. 1.

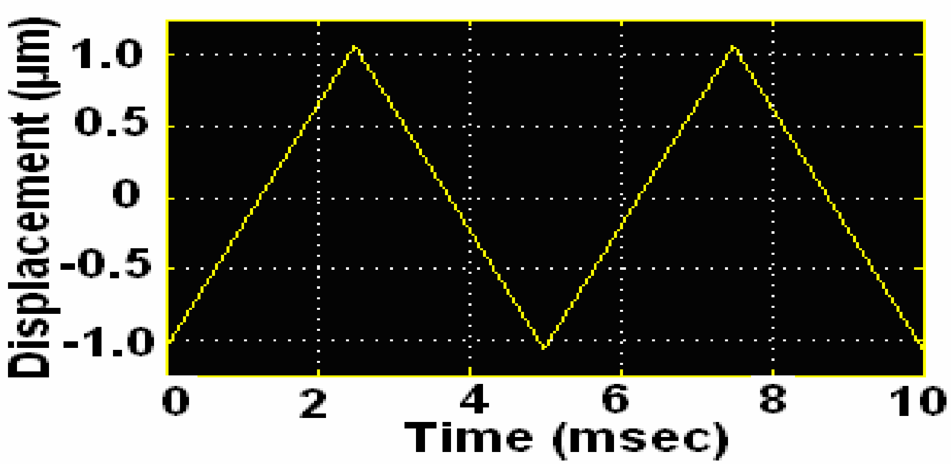


Fig.14 Saw tooth shaped displacement command as input.

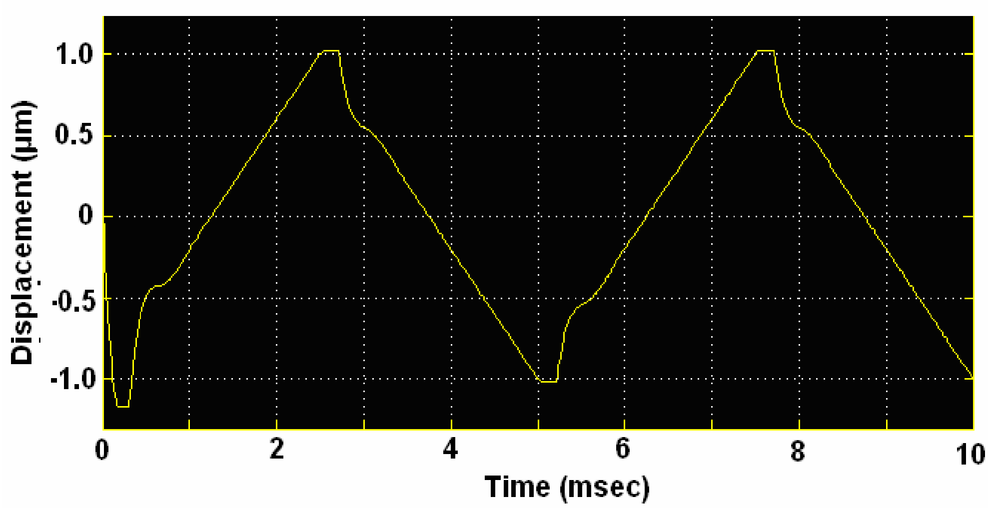


Fig.15 Previous design output of case 1 in Fig. 1.

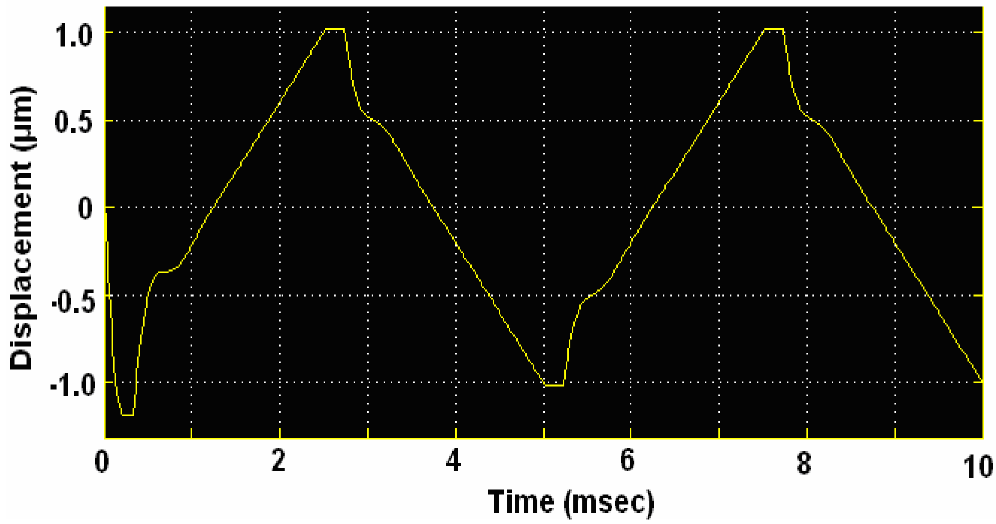


Fig.16 Previous design output of case 2 in Fig. 1.

Now consider the second previous design without LVT for inner-loop feedback in Fig.6. Table 2 also listed the inner and outer loop gains. In addition, the gain margin, phase margin and ω_c are also included. The Bode plots for cases of 1, 3, 4 and 8 are in Figs.19-22 for comparison. In addition, the outputs for saw tooth-shaped input are in Figs. 23-26 (D = 0.3).

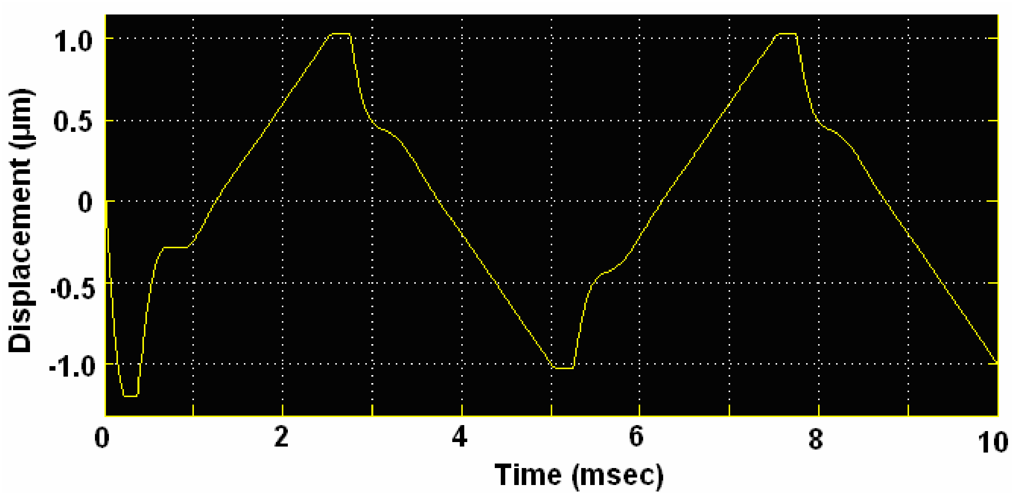


Fig.17 Previous design output of case 5 in Fig.1.

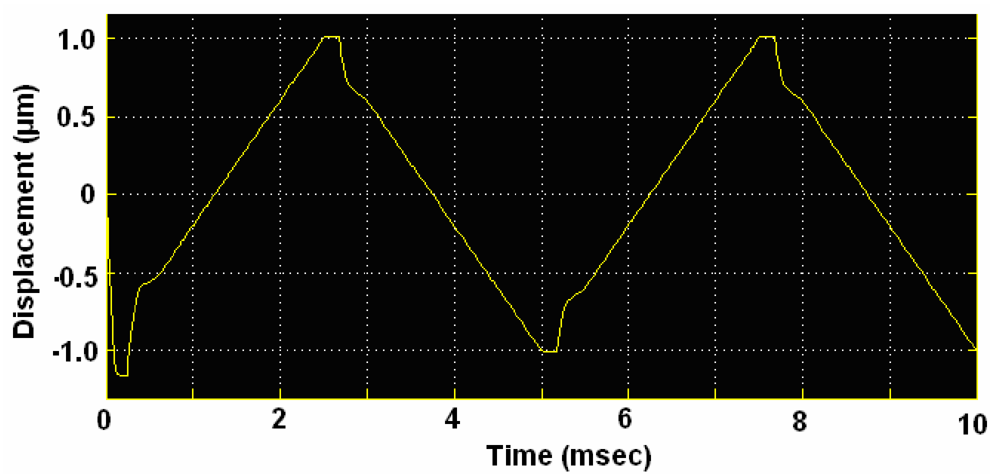


Fig.18 Previous design output of case 6 in Fig.1.

Table 2 The design results of system in Fig.2.

Case	K1	K2	K3	K4	GM	PM (Deg)	ω_c (rad/sec)
1	1	0	1	200	∞	109	80
2	0.5	0	1	200	∞	100	40
3	0.25	0	1	200	∞	98	20
4	0.1	0	1	200	∞	90	8
5	1	0.2	1	200	∞	110	90
6	0.5	0.4	1	200	∞	92	30
7	0.25	0.6	1	200	∞	89	20
8	0.1	0.8	1	200	∞	50	9

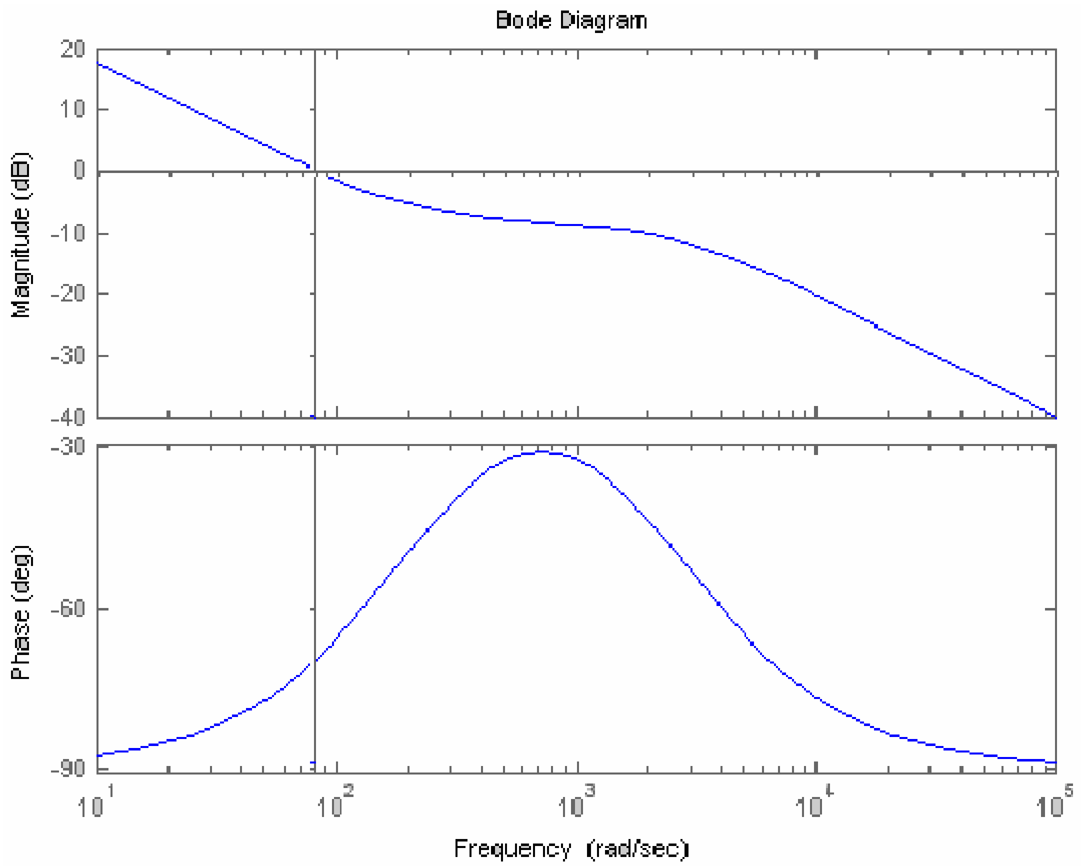


Fig.19 Previous Bode plot of case 1 in Fig.2.

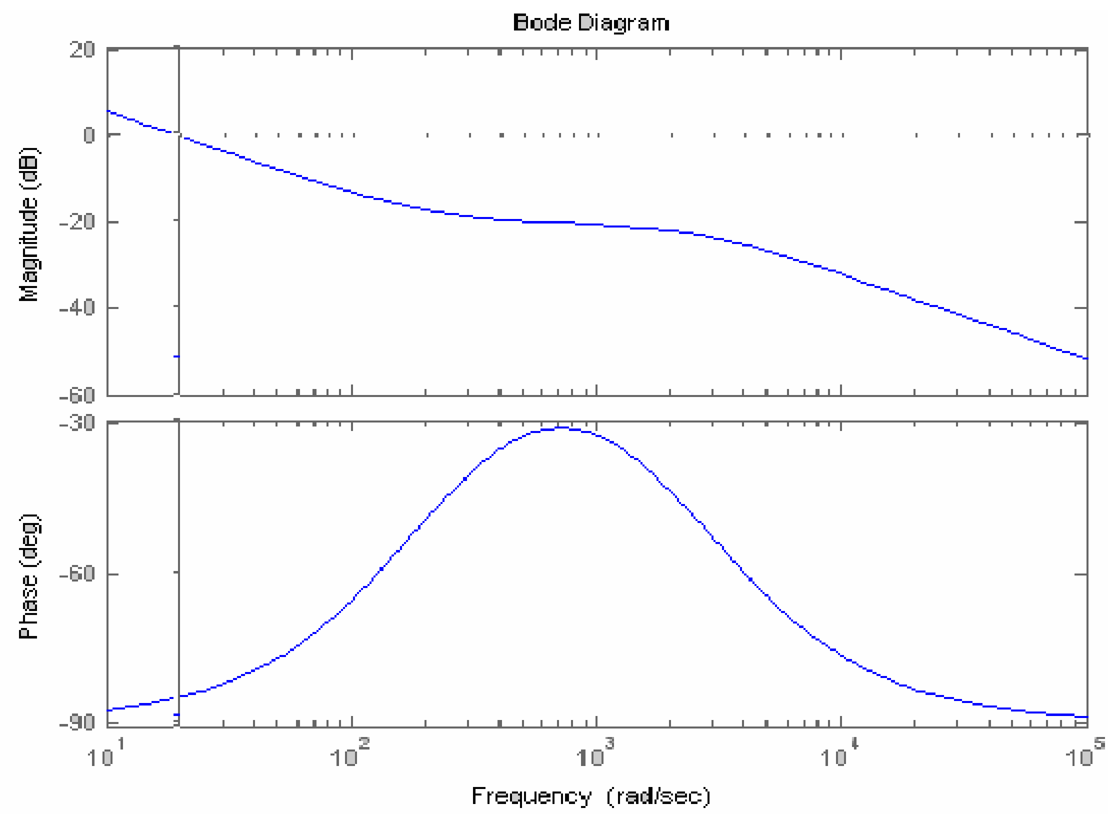


Fig.20 Previous Bode plot of case 3 in Fig.2.

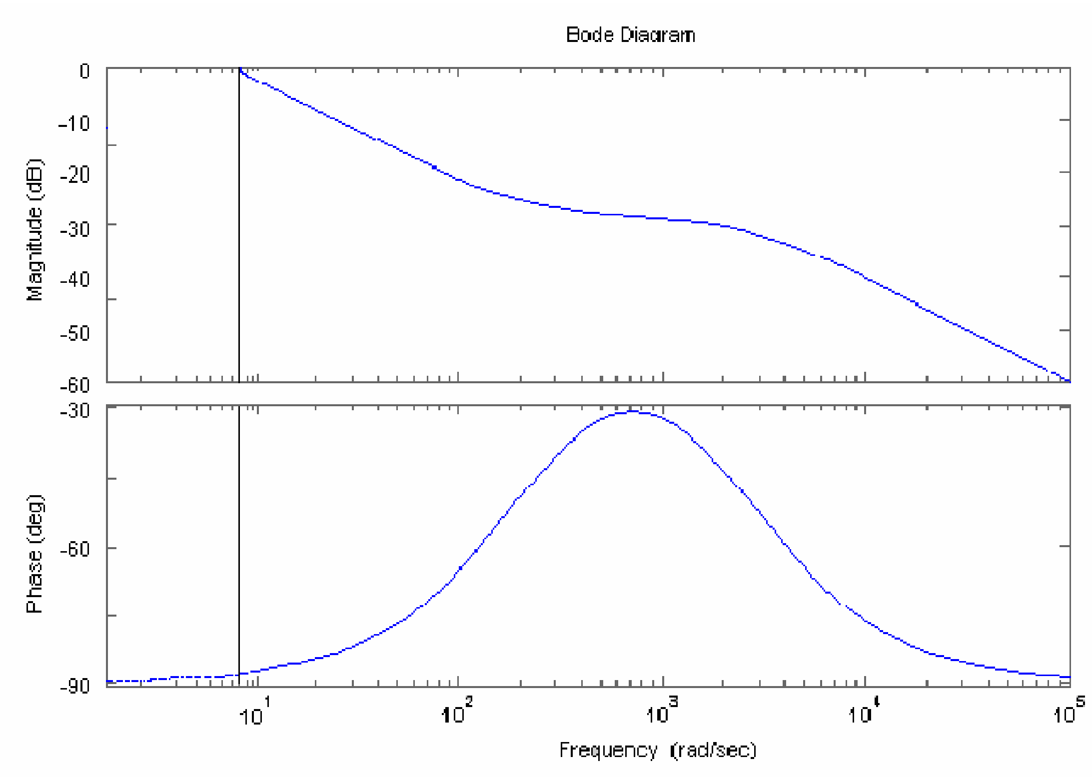


Fig.21 Previous Bode plot of case 4 in Fig.2.

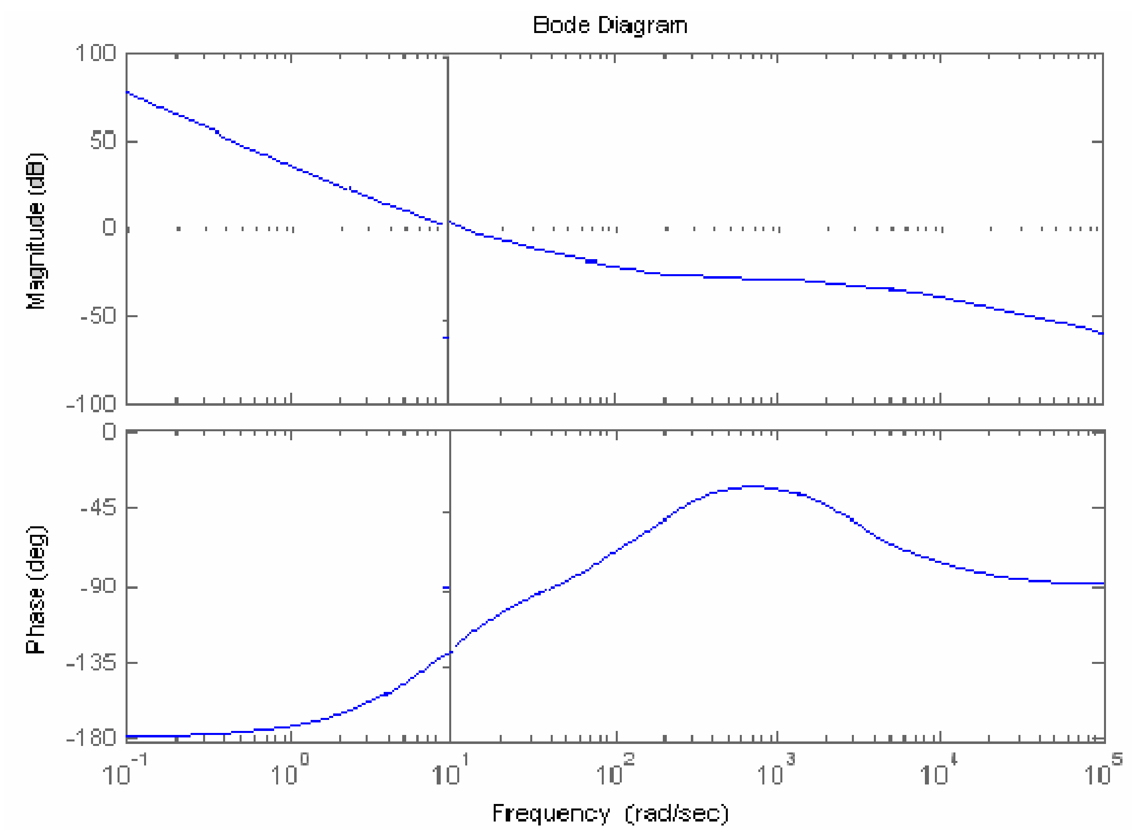


Fig.22 Previous Bode plot of case 8 in Fig.2.

One can see the hysteresis effect is lower for case 1 with larger phase margin, while still bad for cases 3, 4 and 8. The reason is that the phase margins as well as the magnitudes of ω_c are larger for case 1, thus the system responses are quicker, and the dead zone effect and phase delay produced by the hysteresis effect would be smaller as in Fig.23. However, the magnitudes of ω_c as well as the phase margin are much smaller for cases 3 and 4, thus the hysteresis effects are larger as in Figs.24 and 25. In addition, since the original phase margin as well as the magnitudes of ω_c are too smaller of case 8, thus as Fig.26 shows that the stability can even be degraded by adding the hysteresis effect to push the phase margin approaching zero.

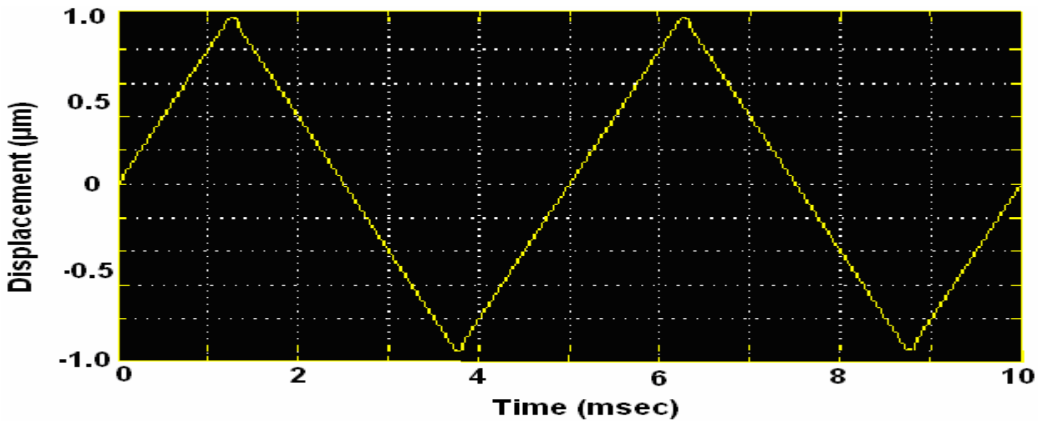


Fig.23 Previous design output of case 1 in Fig.2.

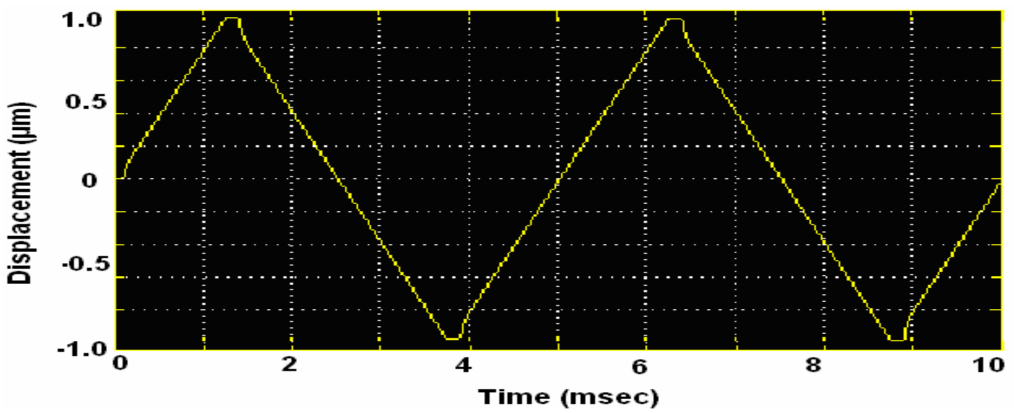


Fig.24 Previous design output of case 3 in Fig.2.

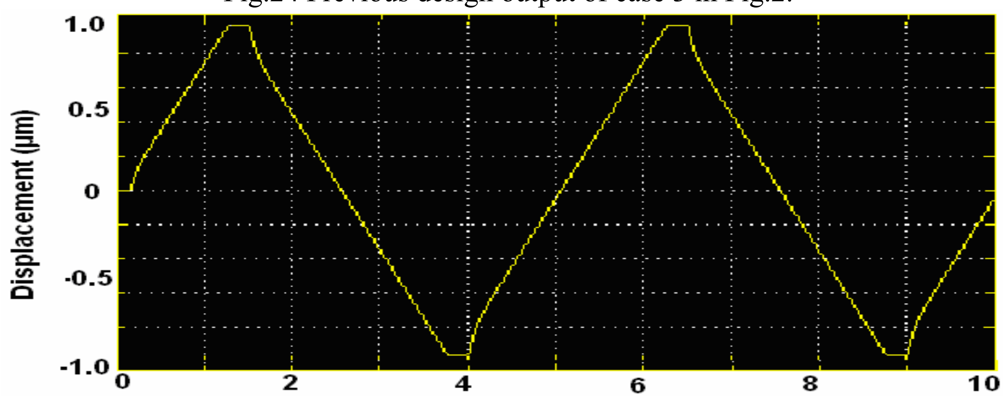


Fig.25 Previous design output of case 4 in Fig.2.

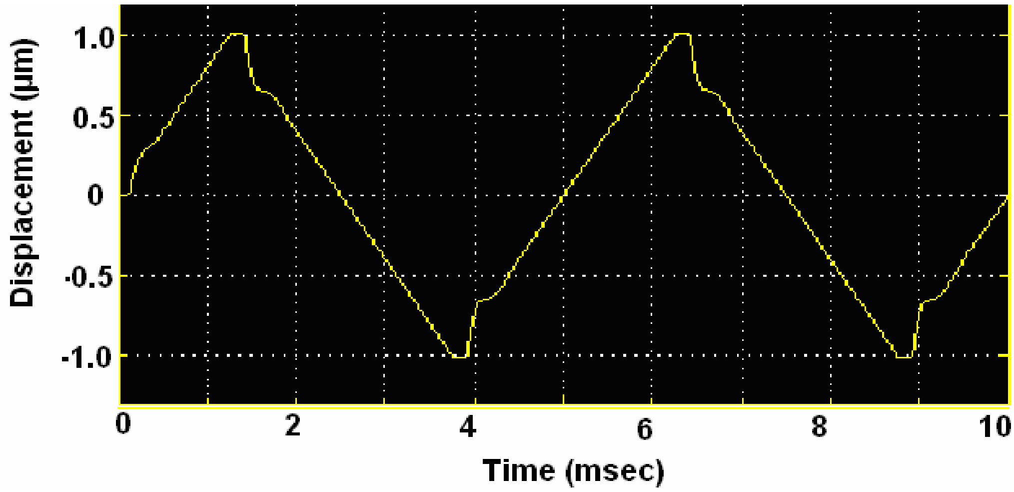


Fig.26 Previous design output of case 8 in Fig.2.

3 Fuzzy Controller Design

3.1 Relationship Functions Design

In this section a Proportion and Derivative (PD) type fuzzy controller [14-18] is applied in the forward loop as in Fig. 3. It is well-known that fuzzy controller is based on the IF-THEN RULE as follows:

R1: IF E is NB AND ΔE is NB THEN U is NB,
R2: IF E is NB AND ΔE is ZE THEN U is NM,
R3: IF E is NB AND ΔE is PB THEN U is ZE,
R4: IF E is ZE AND ΔE is NB THEN U is NM,
R5: IF E is ZE AND ΔE is ZE THEN U is ZE,
R6: IF E is ZE AND ΔE is PB THEN U is PM,
R7: IF E is PB AND ΔE is NB THEN U is ZE,
R8: IF E is PB AND ΔE is ZE THEN U is PM,
R9: IF E is PB AND ΔE is PB THEN U is PB,

where NB, NM, NS, ZE, PS, PM, and PB respectively stand for negative big, negative middle, negative small, zero, positive small, positive middle, and positive big. The detailed cross reference rules for the inputs and the outputs of fuzzy controller are defined in Table 3. According to fuzzy control design method the relationship functions of error E, ΔE (deviations of present E and the previous E), and U (control input) are defined at first, which are listed in Table 4 and shown in Figs.27-29. To reduce the computation time the triangular distribution functions are applied in fuzzy controller relationship functions calculation instead of using the traditional Gaussian ones.

Table 3 Fuzzy controller cross reference rules.

E /Δ*E*	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NM	NM	NS	NS	ZE
NM	NB	NM	NM	NS	NS	ZE	PS
NS	NM	NM	NS	NS	ZE	PS	PS
ZE	NM	NS	NS	ZE	PS	PS	PM
PS	NS	NS	ZE	PS	PS	PM	PM
PM	NS	ZE	PS	PS	PM	PM	PB
PB	ZE	PS	PS	PM	PM	PB	PB

Table 4 Relationship functions of E, ΔE and U.

Item	Parameter E	Parameter ΔE	Parameter U
Negative Big (NB)	[-1 -1 -0.75 -0.3]	[-4.5 -4.5 -3.375 -1.35]	[-12 -12 -9.6 -8.4]
Negative Medium (NM)	[-0.75 -0.3 -0.15]	[-3.375 -1.35 -0.72]	[-9.6 -8.4 -7.2]
Negative Small (NS)	[-0.15 -0.1 0]	[-1 -0.5 0]	[-8.4 -4.8 0]
Zero (ZE)	[-0.05 0 0.05]	[-0.25 0 0.25]	[-4.8 0 4.8]
Positive Small (PS)	[0 0.1 0.15]	[0 0.5 1]	[0 4.8 8.4]
Positive Medium (PM)	[0.15 0.3 0.75]	[0.72 1.35 3.375]	[7.2 8.4 9.6]
Positive Big (PB)	[0.3 0.75 1 1]	[1.35 3.375 4.5 4.5]	[8.4 9.6 12 12]

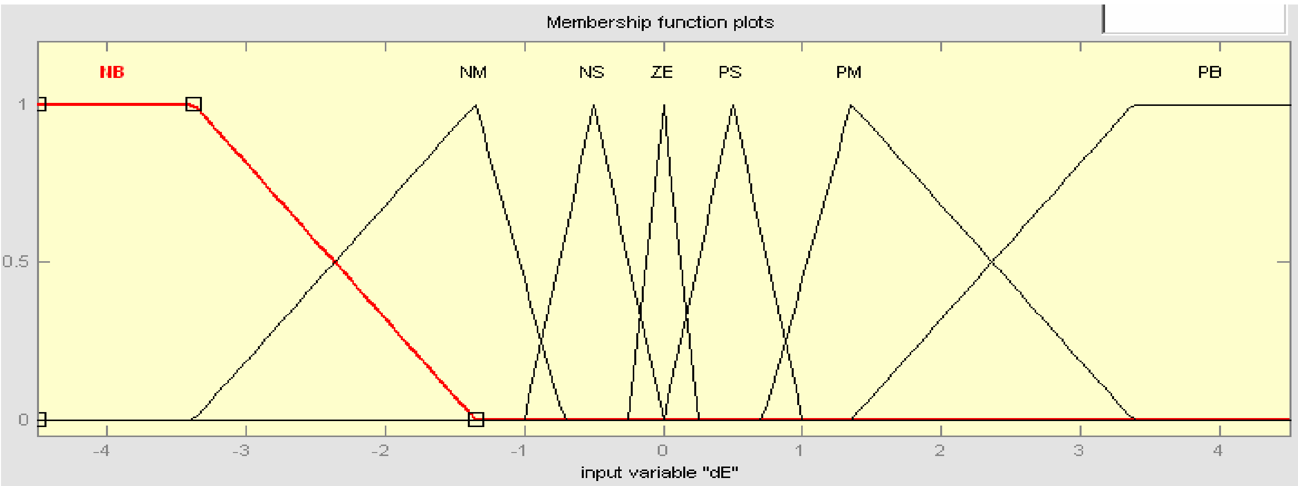


Fig.27 Relationship functions of error E.

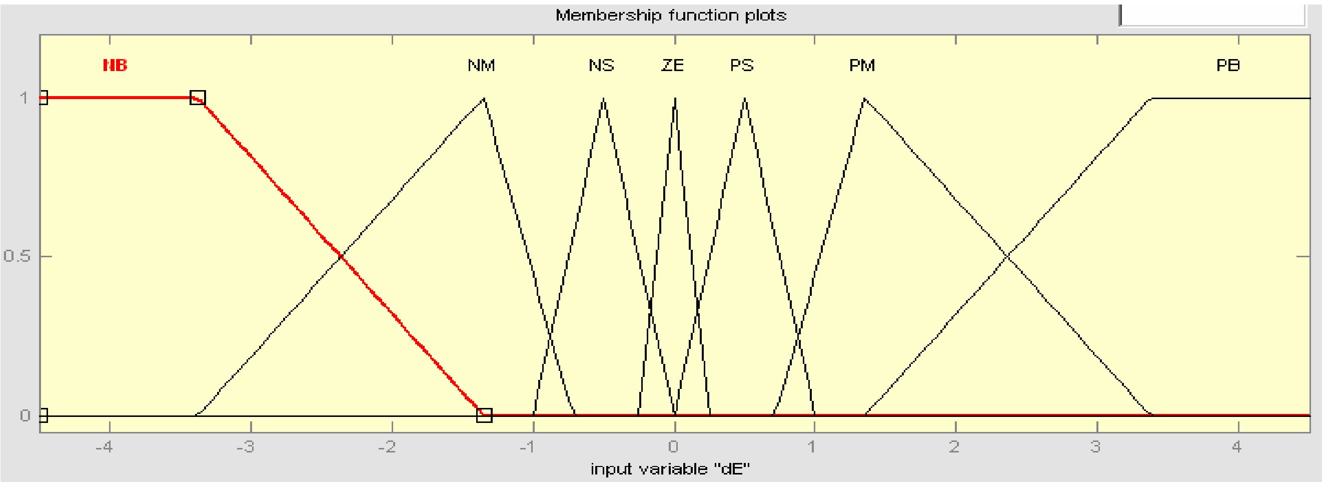


Fig.28 Relationship functions of error rate ΔE.

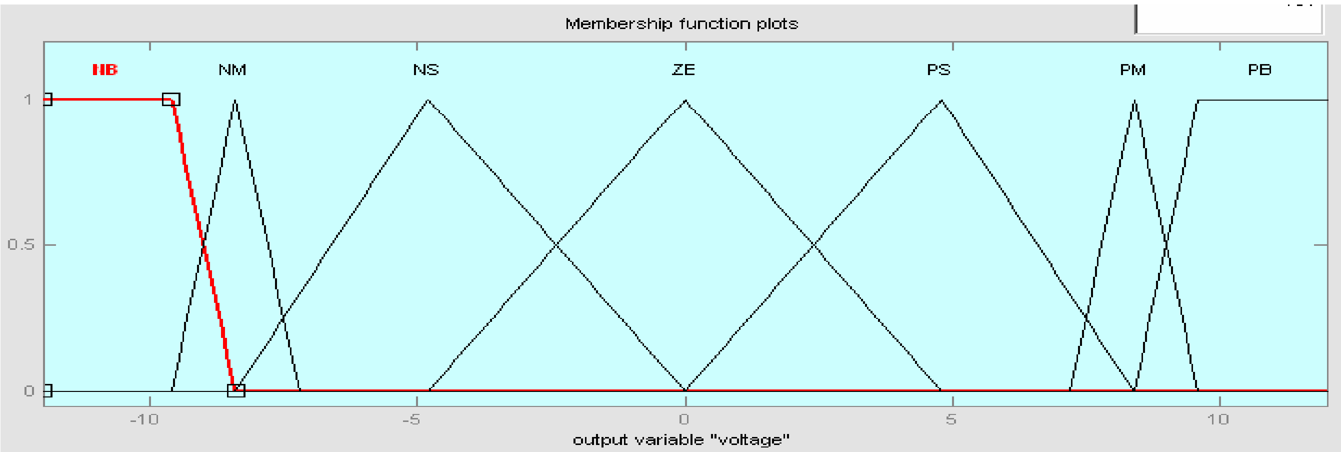


Fig.29 Relationship functions of fuzzy controller output.

3.2 Fuzzy Controller Performance Analysis

Fig 30 shows the response (D = 0.3). It can be seen that the hysteresis effect is almost disappeared, so that this method is better than those obtained by the previous PI controllers. However, there are some chattering effects and can be accomplished by sliding mode control methods [16-18], the result is as in Fig.31.

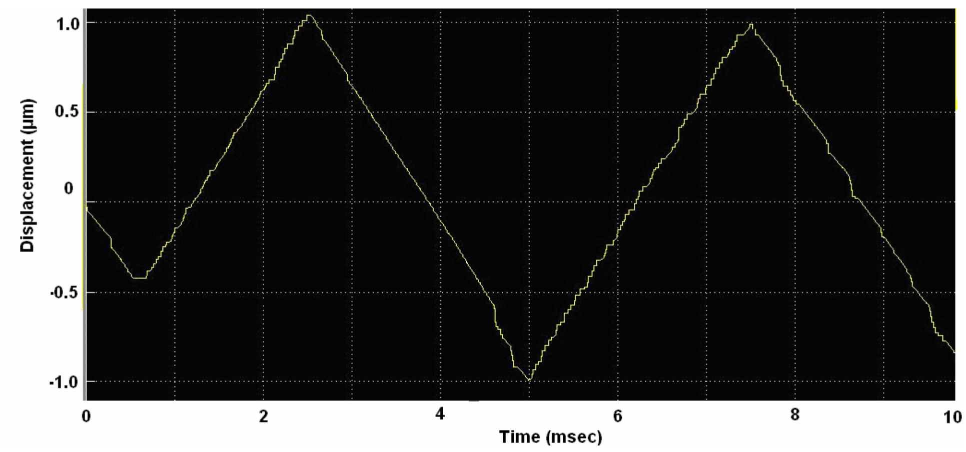


Fig.30 The output response with fuzzy controller.

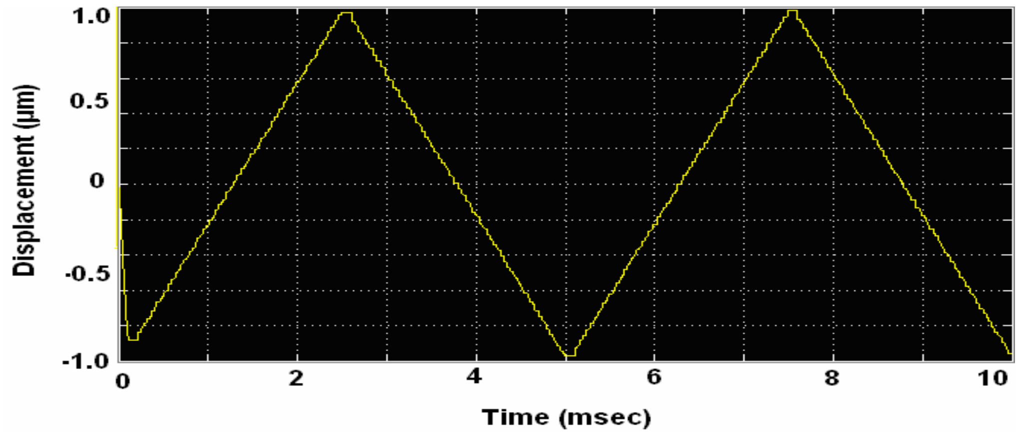


Fig.31 The output response obtained by using fuzzy controller and sliding mode control method.

4 Test Results and Discussions

The signal flow graph of the operation steps is shown in Fig. 32 and summarized as follows. The operation steps are summarized as follows. 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 100 mg. 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.

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. This adjustment process stops when the value of load cell output increases from 0 mg to 100 mg as shown in Fig.33, 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 Figs.34 (a) and (b) for side view and top view, respectively. For comparison purpose a commercial profiler (ET-4000) was also applied, the surface profile of which was shown in Fig.35. Thus one can see that the performance of the proposed system was very good.

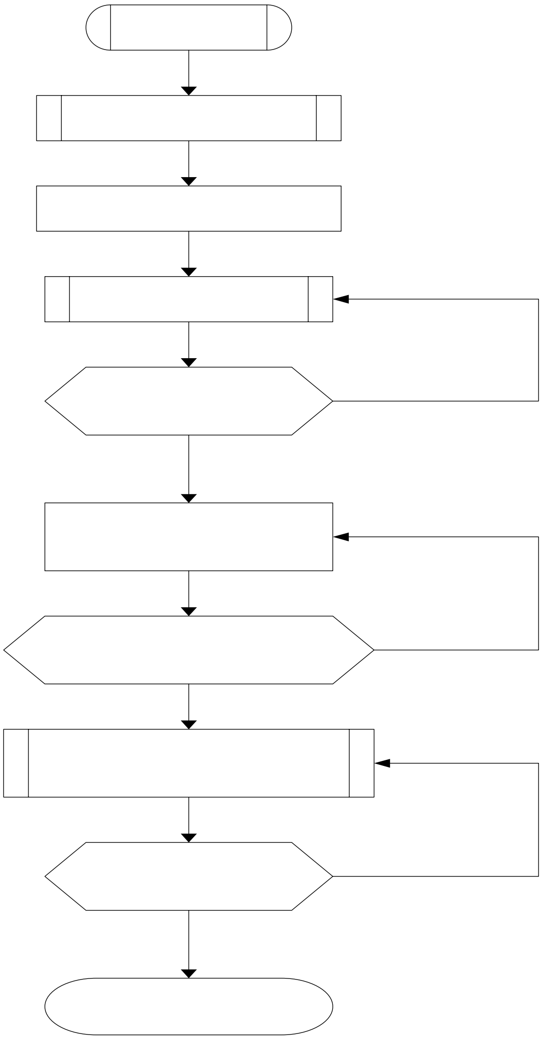
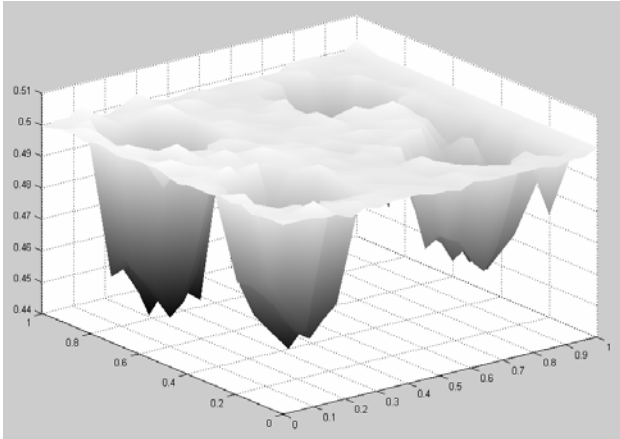
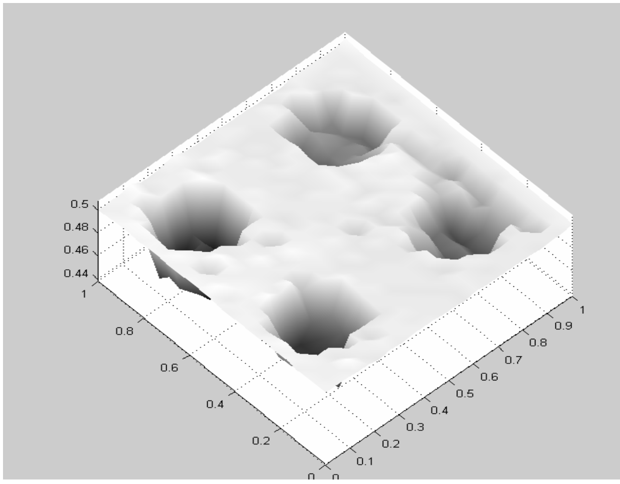


Fig.32 The signal flow graph of the operation steps.



(a) Side view



(b) Top view

Fig.34 The surface profile of a sample obtained by the proposed method.

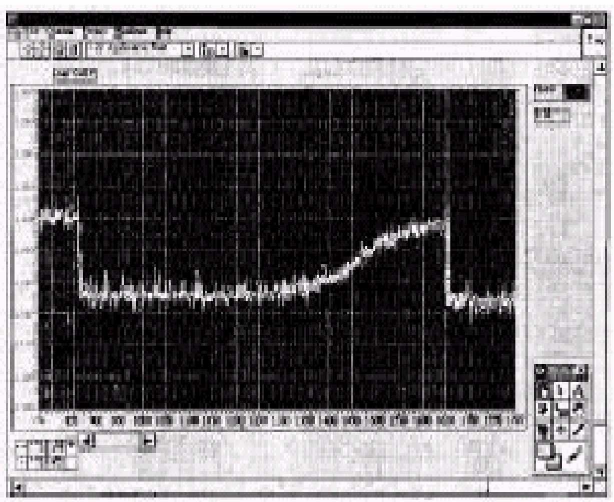


Fig.33 Output voltage of load cell is increased for contact force changing from 0 mg to 100 mg.

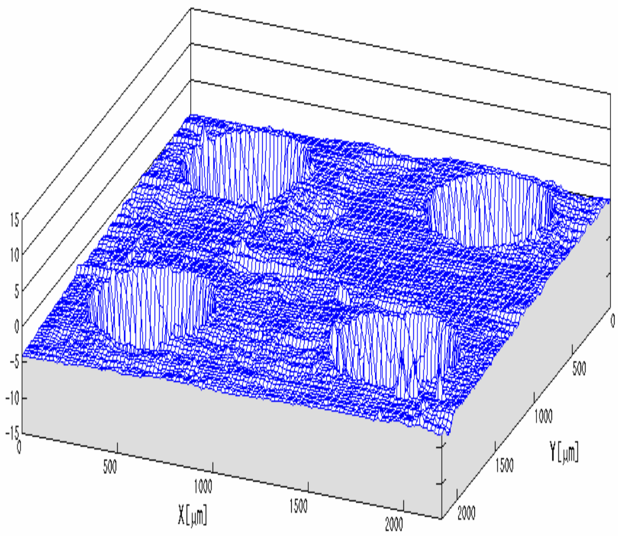


Fig.35 Surface profile of a BGA substrate with a commercial profiler (ET-4000).

5 Conclusion

This research applied fuzzy control method for a Scanning Probe Microscope (SPM) system design. In addition, the actuator hysteresis effect was taken into consideration. Comparisons with two previous works with and without Linear Velocity Transducer (LVT) for inner-loop feedback compensation are also made, it can be seen that the system performance obtained by the fuzzy controller is much better, especially in eliminating the actuator hysteresis effect. This improvement has been verified by MATLAB simulation and practical implementation of a surface profiler. Finally, the profile of the object surface is displayed on a 3D graph.

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