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Design & modeling a novel Atomic Force Microscope (AFM) for detect roughness in turning machining

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Abstract. In this paper we design and modeling a novel AFM (Atomic Force Microscope) that use it in turning machining. We know that work piece roughness is very essential part in final product in every machining method specially in turning. In this case we want to know availability of using AFM in turning. So at first designed a kind of AFM with cantilever beam, piezoelectric and piezoresistance. After that we should modeling this design in our situation, for these we define some surface that may be happen in machining. So know modeled our design for sample surface. At the end of project a P control method has been used for controlling our processing.

Keywords: Atomic Force Microscope; turning machining; roughness; AFM control; cantilever beam

1. INTRODUCTION

The atomic force microscope (AFM) is a very important instrument for exploring materials at the scale of a few nanometers [1]. AFM is an instrument which measures the topography of a surface by bringing a cantilever beam into contact with a sample and measuring the deflection of the cantilever as it is scanned across the surface [2]. The complexity of an AFM is predominantly governed by the detector used for measuring the deflection of the cantilever probe [2]. At the heart of this instrument is a cantilever probe that sets the fundamental limitations of the AFM.

The primary key to improved cantilevers is to make them thinner and shorter, for increased force resolution and bandwidth. A fabrication technique using epitaxially grown piezoresistors to reduce cantilever thickness a factor of four below the thinnest implanted piezoresistors. The atomic force microscope uses a micromachined cantilever probe to measure forces and displacements with nanometer precision and sub-nano-Newton force resolution. In its typical configuration, a micromachined silicon or silicon nitride cantilever with an atomically sharp tip is mounted on a piezoelectric actuator. The actuator allows positioning and scanning of the tip over 10s to 100s of microns with sub nanometer resolution, and is used to raster scan the tip across the surface. Forces on the tip that cause deflection of the cantilever can be measured to create an image of the surface [3].

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Piezoresistive are widely used in commercial pressure sensors and accelerometers. A stretched wire grows longer and thinner, which increases its resistance from geometry alone. Any conducting material can act as a strain gauge by this geometrical mechanism, but piezoresistive sensing usually refers specifically to strain gauges in semiconductors. The electrical properties of some doped semiconductors respond to stress with resistance changes over 100 times greater than those attributable to geometric changes alone. Piezoresistors in silicon are created by introducing dopant atoms to create a conducting path. When the silicon experiences stress, and therefore strain, the lattice spacing between the atoms changes, affecting the band-gap energy. This band-gap change either increases or decreases the number of available carriers in the doped region, which is measured as a change in resistance20. A further advantage of piezoresistors is that the minimum size constraint associated with optical cantilevers is avoided. Reducing cantilever size allows for a simultaneous increase in bandwidth and decrease in the spring constant, key advances for increased performance [3].

Most current piezoresistive cantilever applications are focused on developing large cantilever arrays, and cantilevers with high bandwidth. A major criticism of AFM based imaging is that the serial nature of reading with a single tip makes it too slow for fast, large area scans [3].

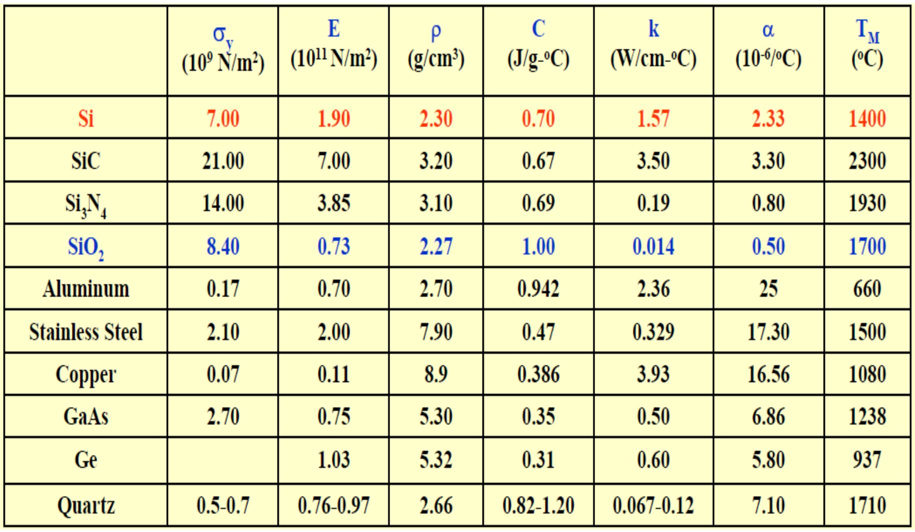
The goal of any sensor is to measure signals of interest in the presence of noise, and to do so on a time scale commensurate with the signal. Furthermore, the sensor cannot be too obtrusive during the measurement, and thereby affect the signals or change the environment. A large response to a small signal is clearly beneficial to the performance of a sensor, and is measured as the sensitivity. The output without an input signal is the noise. Resolution is defined as the noise divided by the sensitivity, and is a measure of the smallest resolvable signal. It should therefore be as small a number as possible. The frequency range of the signals that can be measured is the bandwidth, and is related to the speed of the sensor, as well as the sampling rate and the total length of the measurement. Finally, for an AFM cantilever, the spring constant of the beam will determine how it interacts with its environment [3].

2. DESIGN

A. Mechanical design

The main shape is a cantilever beam that made of silicon, the property of silicon exists in table 1, this mechanism has a piezoresistor for sensor and piezoelectric as an actuator, and property of these piezoresistor and piezoelectric have been shown in table 2.

Table 1. Principal source for semiconductor material properties: "Fundamentals of Microfabrication", Marc Madou, CRC Press, 1997. Legend: σ_y = yield strength; E = Young's modulus; ρ = mass density; C = specific heat; k = thermal conductivity; α = coefficient of thermal expansion, TM = melting point.



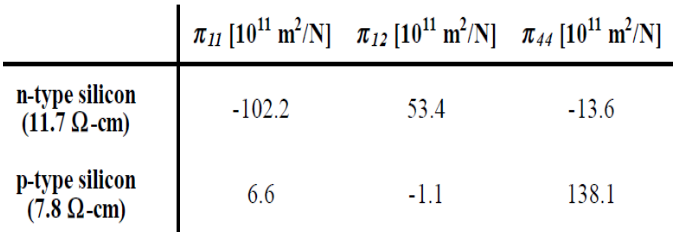
	σ_y (10^9 N/m^2)	E (10^{11} N/m^2)	ρ (g/cm^3)	C (J/g-°C)	k (W/cm-°C)	α (10^{-6}/°C)	T_M (°C)
Si	7.00	1.90	2.30	0.70	1.57	2.33	1400
SiC	21.00	7.00	3.20	0.67	3.50	3.30	2300
Si_3N_4	14.00	3.85	3.10	0.69	0.19	0.80	1930
SiO_2	8.40	0.73	2.27	1.00	0.014	0.50	1700
Aluminum	0.17	0.70	2.70	0.942	2.36	25	660
Stainless Steel	2.10	2.00	7.90	0.47	0.329	17.30	1500
Copper	0.07	0.11	8.9	0.386	3.93	16.56	1080
GaAs	2.70	0.75	5.30	0.35	0.50	6.86	1238
Ge		1.03	5.32	0.31	0.60	5.80	937
Quartz	0.5-0.7	0.76-0.97	2.66	0.82-1.20	0.067-0.12	7.10	1710

Actuator is a tube that one side is attached to the lever of mechanism and the other side is attached to the cantilever. This actuator is able to move the beam up and down. In piezoresistor, a change is resistance is usually, converted into a voltage by using a Wheatstone bridge followed by an instrumentation on amplifier.

$$\frac{\Delta\rho}{\rho} = \pi_1 \sigma \tag{1}$$

$$\pi_1 = \pi_{11} - 2(\pi_{11} - \pi_{12} - \pi_{44})\Gamma \tag{2}$$

Table 2. Piezoresistor design parameters.



	π_{11} [10^{11} m^2/N]	π_{12} [10^{11} m^2/N]	π_{44} [10^{11} m^2/N]
n-type silicon (11.7 Ω-cm)	-102.2	53.4	-13.6
p-type silicon (7.8 Ω-cm)	6.6	-1.1	138.1

The formulation of spring constant and resonant frequency of beam can be calculate by

K = (E.W.T^3)/4.L^3 (3)

We have constant force 1nN at the tip of cantilever and the amount of stress in the base of cantilever can calculate by:

σ=12(L-y) c/ (W* t^3)*F (4)

Produced Output voltage by piezoresistor sensor, calculated with below equation

$$V\_out= (\Delta R/R) (V\_bias/4) \tag{5}$$

That (6) is the sensitivity of cantilever that calculated by

$$\Delta R/R= (6^* \pi^*L (L-L\_leg/2))/ (W^* t\hat{}3)^*F \tag{6}$$

And bias voltage is 5 volt. The relation between length difference and operating voltage is shown by

$$\Delta L = d_{31}{}^*L * U/d \tag{7}$$

In addition for display applied design we used CATIA software and trace turning machining and location of AFM

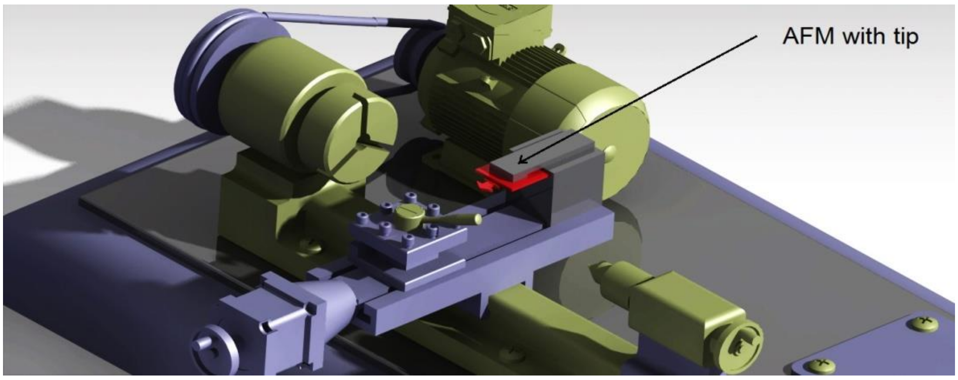


Figure 1. AFM that modeled for lathe in CATIA.

B. Cantilever Vibration

In some cases if we have same excitation in the work space, we can model this excitation by free vibration in the cantilever beam. By considering the equation of vibration and initial and boundary condition exposed in (8) and (9), by considering the first 5 mode shape of cantilever are modeled in figure 2. We should design a suitable filter to separate them from original signal.

$$M (\partial\hat{}2\ y)/ (\partial t)\ \hat{}2 + EI (\partial\hat{}4\ y)/ (\partial x)\ \hat{}4 =f (x, t) \tag{8}$$

$$y(0,t)=\ \partial y/\partial x\ (0,t)= (\partial\hat{}2\ y)/(\partial x)\hat{}2\ \ (L,t)= (\partial\hat{}3\ y)/(\partial x)\hat{}3\ \ (L,t)= 0 \tag{9}$$

We were able to provide the first five shape modes by same arbitrary values in MATLAB software:

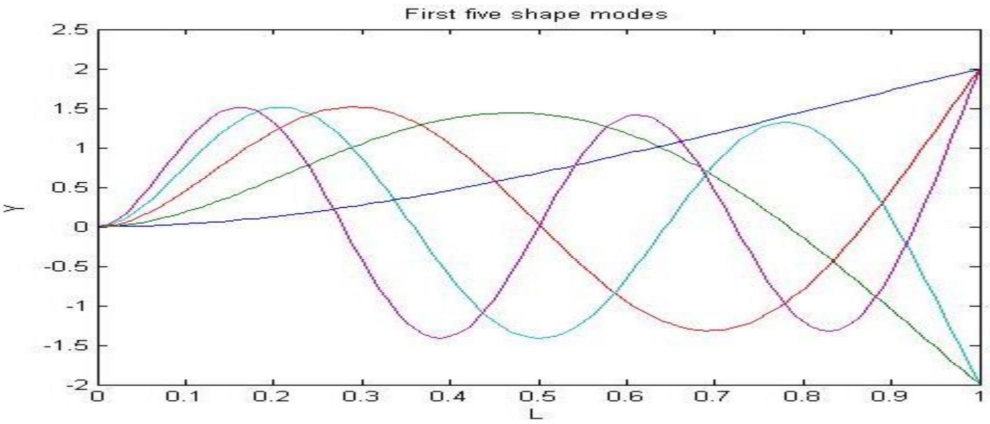


Figure 2. First five shape modes in free vibration.

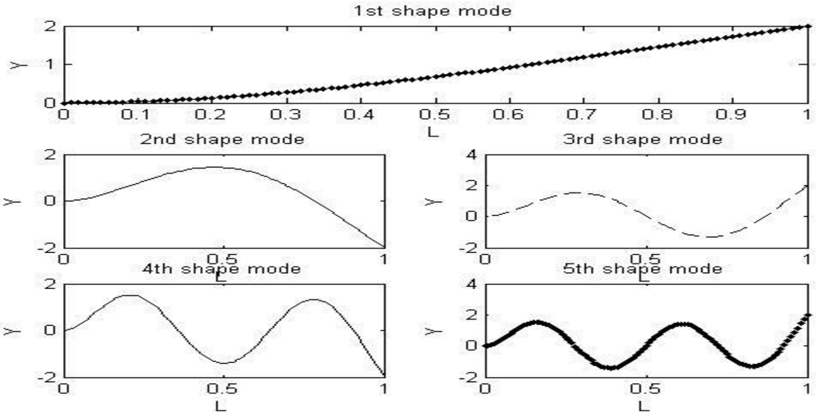


Figure 3. Five shape mode for cantilever in free vibration.

3. FABRICATION

We use fabrication method that developed by Tortones et al. In figure 5 at first we have a bulk of silicon and cantilever and leads are etched in top of silicon and top silicon is boron doped and after that metal leads are deposited then wafer is etched from the back side, stopping on the oxide and finally the oxide is removed and release the cantilever. Tip of beam is made by epistaxis.

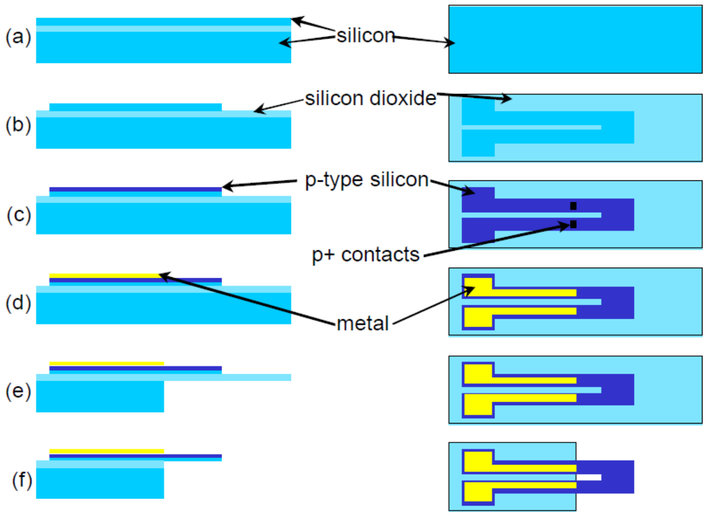


Figure 4. Fabrication method for AFM.

4. AFM CONTROL

Simulating of AFM has been done in simulation of MATLAB in figure 6. We use a kind of p controller for control our processing. For input variable we define 3 kind of input; step, sinusoidal and random input. The suitable coefficient of P for 0.2 s response time is about 0.069 and error signal send for actuator for move the beam up and down.

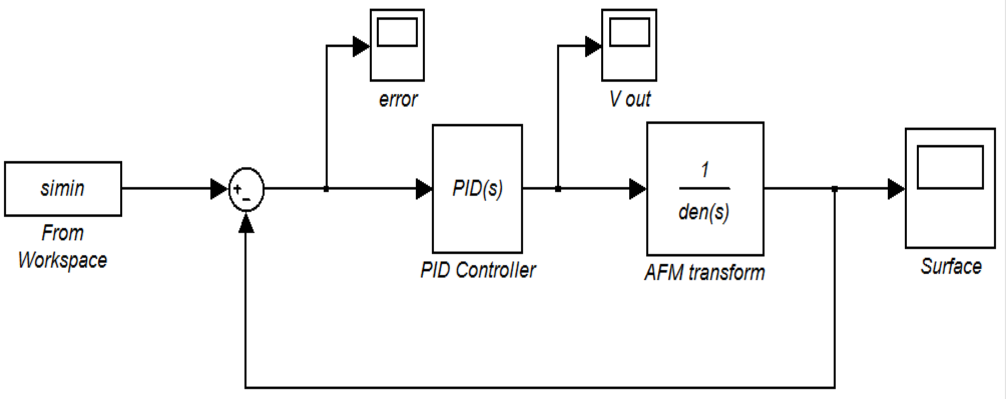


Figure 5. Control diagram that used for AFM with P controller.

5. RESULT & DISCUSSION

The result of output signal simulation sine, step and random input have been shown in figure 7, 10 and 13. Error signal that comes from feedback and send to actuator are shown in figure 8, 11 and 14 for sine, step and random respectively.

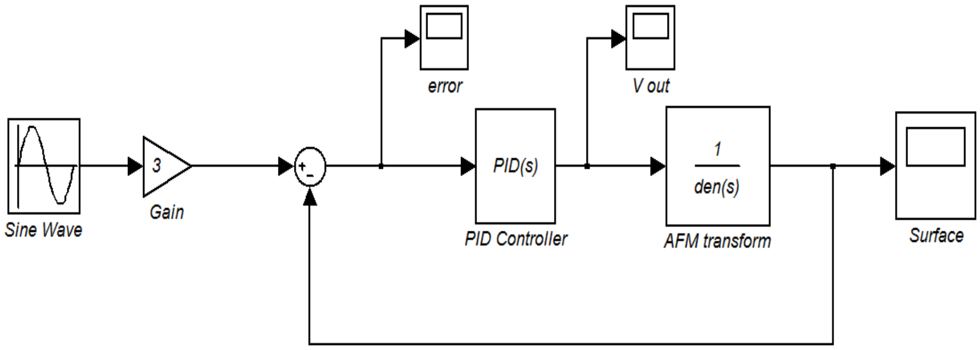


Figure 6. Control diagram for sine wave input.

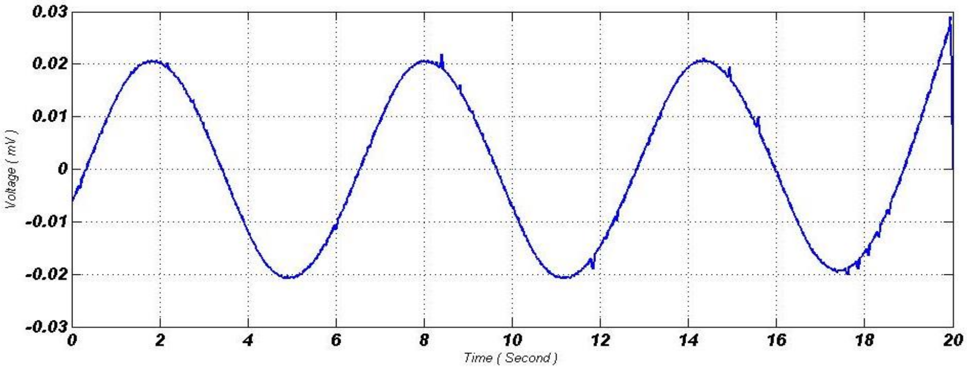


Figure 7. Error plot that achieved from sine wave input.

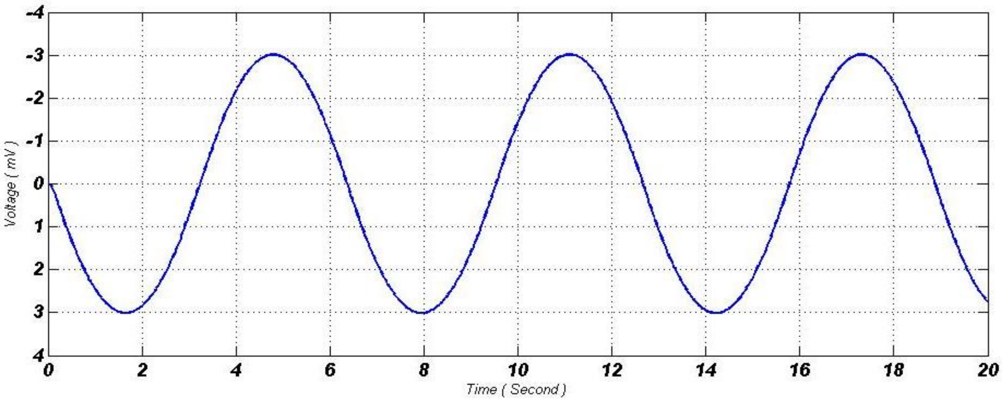


Figure 8. Output plot (surface) that achieved from sine wave input

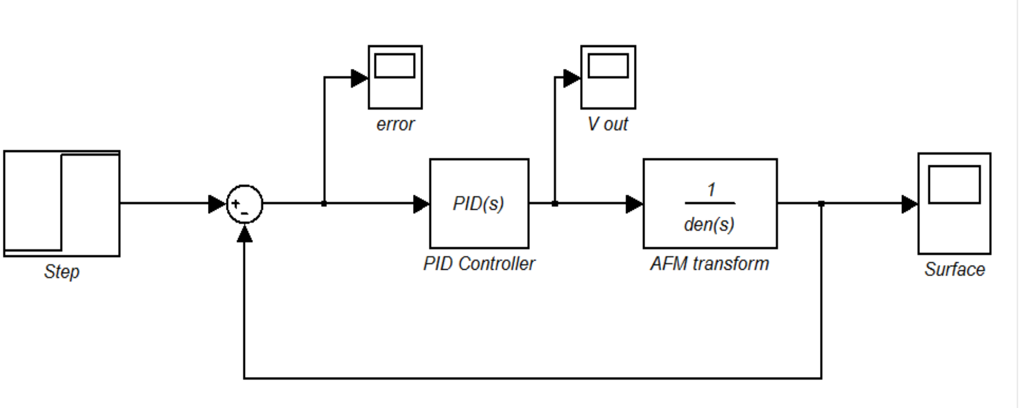


Figure 9. Control diagram for step wave input.

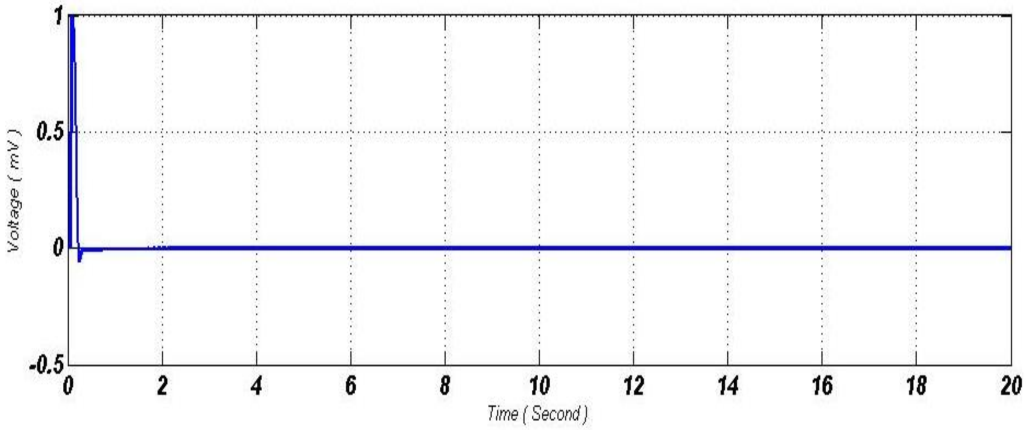


Figure 10. Error plot that achieved from step input.

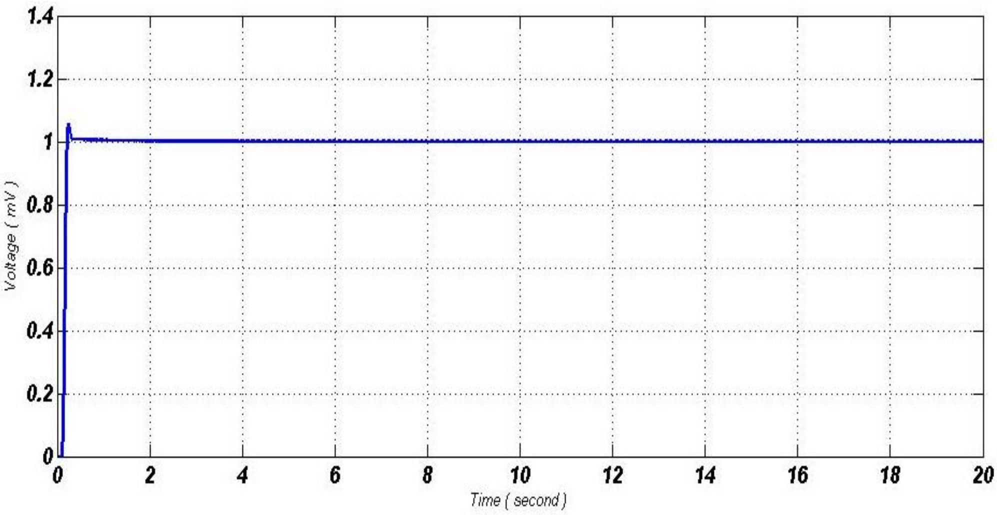


Figure 11. Output plot (surface) that achieved from step input

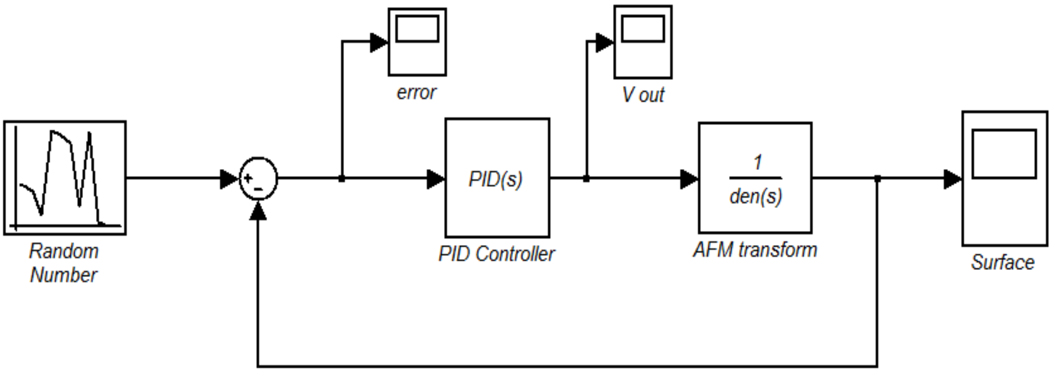


Figure 12. Control diagram for random input.

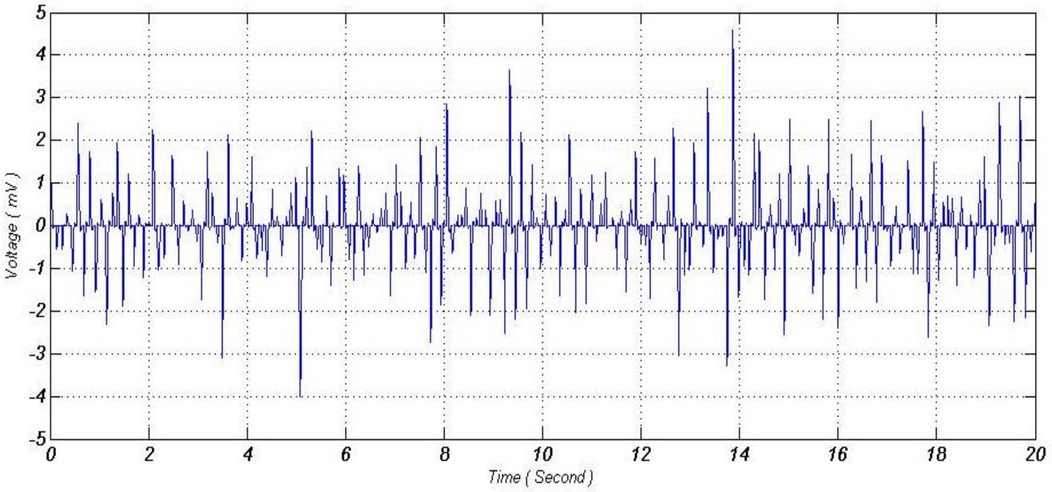


Figure 13. Error plot that achieved from random input.

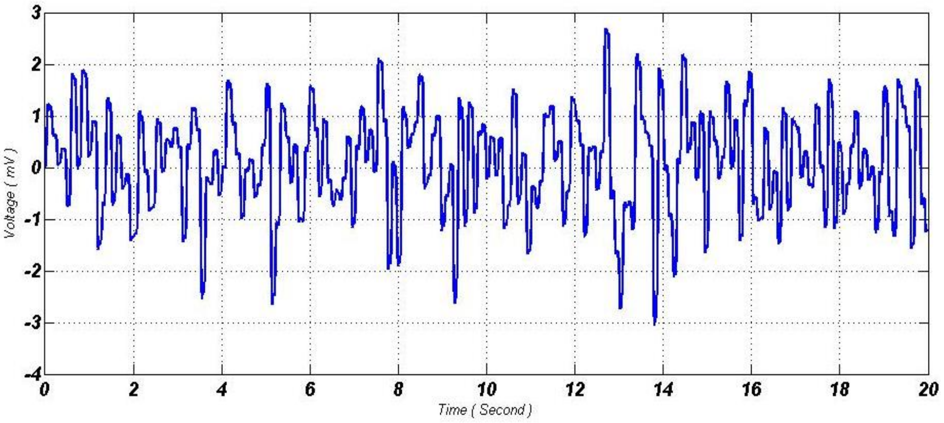


Figure 14. Output plot (surface) that achieved from random input.

6. CONCLUSION

In this work we proposed a novel instrument for surface monitoring of parts in rotating machinery. A one dimensional atomic force microscopy added to machine and the quality of part can be lived measured. The vibration of base of AFM due to machine vibration have been modeled since we have totally 3 kind of roughness On the parts of surface we simulate the voltage generated of a AFM for those this 3 type of roughness. And the result has validated by the quantities of input signals.

The amount of error is an impact function. The configuration of this curve is the result of one change in output exactly in t=1s and we have not any other variation in the other times. The validation of this result again can be shown with good agreement of result by the input in Figure 11.Figure 13 and 14 are show again the error and of random output in 20 seconds and we have a good agreement between result and input.

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