Optimal design of high stiffness XYZ 3-axis stage for AFM system

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Atomic force microscopes(AFM) provide high resolution, 3-D data and are therefore very useful for measurement of micro- and nano-structured objects. To establish of standard technique of nano-length measurement in 2D plane, we are developing AFM system. Because measurement uncertainty of this instrument is dominantly affected by the Abbe's offset error of XYZ stage[1], XYZ flexure stage is designed to have least parasitic motion. In this paper with the object of reducing XYZ stage error, decoupled XYZ stage is suggested and optimal design is performed to maximize its robustness about disturbance. And setup of sensor system is done with the same object.(Fig. 1) 3-axis heterodyne interferometer which is commercial product of Zygo(ZMI 2000) measures the XYZ displacement. Each XYZ beam enters at the same place with the tip. For direct Z axis measurement 90 degree deflection prism below sample is used to deflect the laser beam. Using a prism, instead of a mirror, causes less polarization change. Soon to acquire high accuracy, COXI(Combined Optical and X-ray Interferometer) will substitute for commercial sensor.

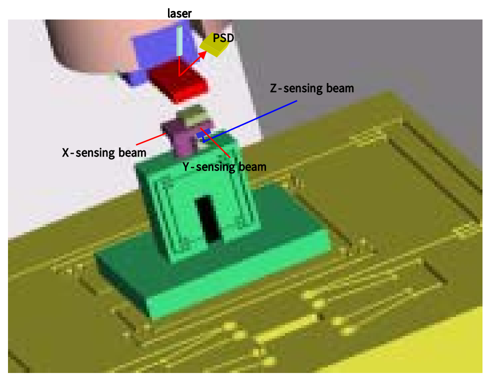


Fig. 1 The configuration of XY stage

For XY stage(Fig. 2(a)), single module parallel-kinnematic flexure stage is used which has high orthogonality and minimum out-of-plane motion. And Z stage(Fig. 2(b)) is proposed to have minimum out-of-plane motion also. Z stage is combined on XY stage. As a result XYZ stage has independent motion.

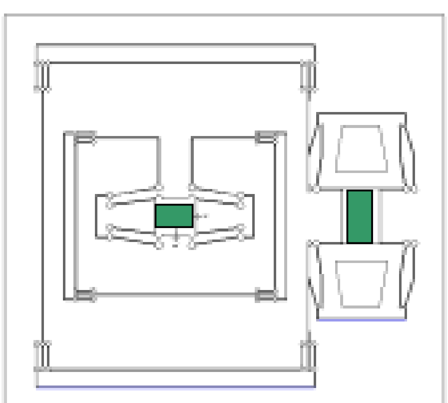

Fig. 2(a) The configuration of XY stage

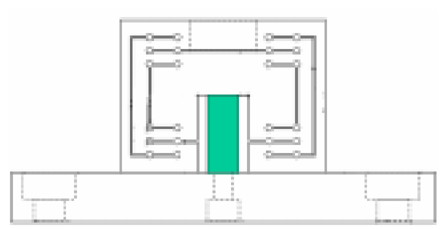

Fig. 2(b) The configuration of Z stage

In X stage magnification structure is used to magnify PZT's motion range(25μm). Y stage has same structure except it is inside X stage. Optimal design is performed to obtain best performance. Before modeling first we simplified model on the basis of FEM simulation to make more practical by reducing design variable. For example, the ratio between width and length of hinge's bar is determined by FEM simulation. Then the method introduced in Ryu's paper[2] is used to obtain dynamic equation. In Fig.3 flow chart of optimal design is shown. By this method the equation of motion is expressed by the function of design variables. Design variables are hinge thickness, hinge radius, distance between hinges and geometry data. The number of design variables 26.

For XY stage, to be robust about parasitic motion, optimal design of maximizing Z and tilt stiffness is performed under the constraint of motion range (110μm, 10% safety factor) and stage size (300mm*300mm). And for Z stage, optimal design of maximizing 1st resonant frequency is performed under the constraint of motion range (15μm, 50% safety factor) and stage size which enables locate on Y stage. If resonant frequency is get higher, scan speed is improved. So it makes reduce the error by sensor drift.

Design results are as follows. XYZ axis motion range is each 110μm, 110μm, 15μm. 1$^{st}$ natural frequency is 115Hz, 201Hz, 2.24kHz. And 6 axis stiffness is shown in Table. 1. From FEM simulation is similar with modeling results, we can verify modeling is reasonable. From FEM simulation, XYZ axis motion range is each 103μm, 105μm, 12μm and the 1$^{st}$ natural frequency is 109Hz, 201Hz, 2.86kHz. From that XY direction natural frequency is very similar but Z direction natural frequency has 46% difference. The reason is that to increase natural frequency in optimal design hinge's thickness is getting higher. So strain energy happens not only flexure hinge but also around flexure hinge(Fig. 4). But in the modeling only hinge stiffness is modeled and other connecting bars are assumed as rigid bodies. By that reason there is difference between modeling and FEM. But with simple model we can find that when increasing hinge's thickness its difference between modeling and FEM is increased linearly. By that fact optimal design is reasonable even if its result is different.

| | |
|---|---|
| $k_x$ (motion dir.) | 2.3(N/um) |
| $k_y$ (motion dir.) | 3.2(N/um) |
| $k_z$ | 27.6(N/um) |
| $k_{\theta x}$ | 92.5(Nm/mrad) |
| $k_{\theta y}$ | 134.2(Nm/mrad) |
| $k_{\theta z}$ | 1018(Nm/mrad) |

Table. 1(a) 6 axis stiffness of XY stage

| | |
|---|---|
| $k_x$ | 2098(N/um) |
| $k_y$ | 470(N/um) |
| $k_z$ (motion dir.) | 47(N/um) |
| $k_{\theta x}$ | 81.9(Nm/mrad) |
| $k_{\theta y}$ | 374.6(Nm/mrad) |
| $k_{\theta z}$ | 255.3(Nm/mrad) |

Table. 1(b) 6 axis stiffness of Z stage

With this optimal results, XYZ flexure stage is fabricated (Fig. 5). Its material is AL 7075.

To confirm XYZ flexure stage is well fabricated frequency response function(FRF) and maximum range test experiment is performed. . As a result it has 1st natural frequency of 103.5Hz, 160Hz, 2.2kHZ(Fig. 7(a)) and range of 106μm, 103μm, 11μm (Fig. 7(c)) in XYZ direction each. Its experimental setup is shown in Fig. 6. And then by laser interferometer feedback(0.31nm resolution) we obtained 1nm stage resolution.

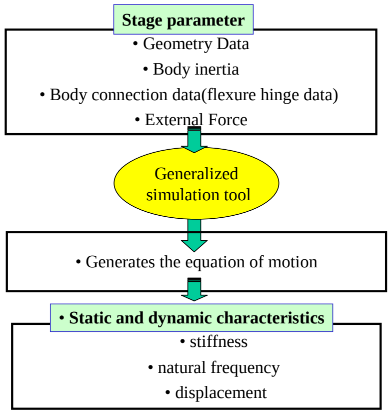


Fig. 3 Flow chart of optimal design

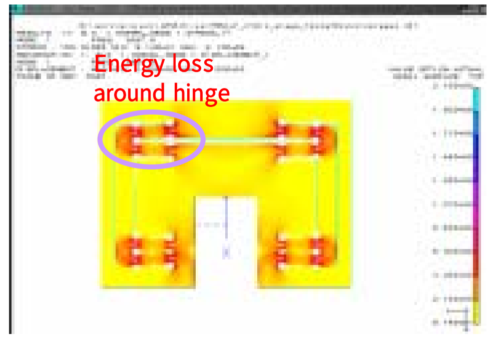


Fig. 4 Energy loss around flexure hinge of Z stage(FEM)

Fig. 5(a)

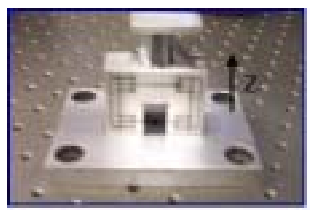


Fig. 5(b)

Fig. 5(c)

Fig. 5 The picture of XYZ stage : (a) XY stage, (b) Z stage, (c) XYZ stage

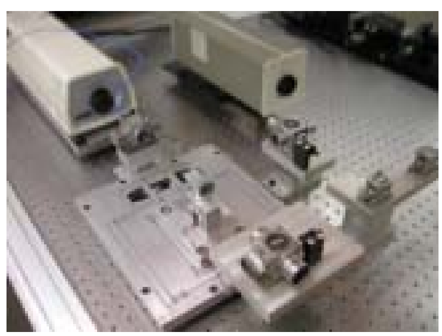

Fig. 6 Experimental setup of XYZ stage

Soon, total AFM system will be completed. Then total measurement uncertainty will be evaluated. By this stage we expect to reduce abbe's offset error because this stage has very low out-of-plane motion. Out final goal is to measure 2-D pitch with 3nm uncertainty about 100 μm × 100 μm.

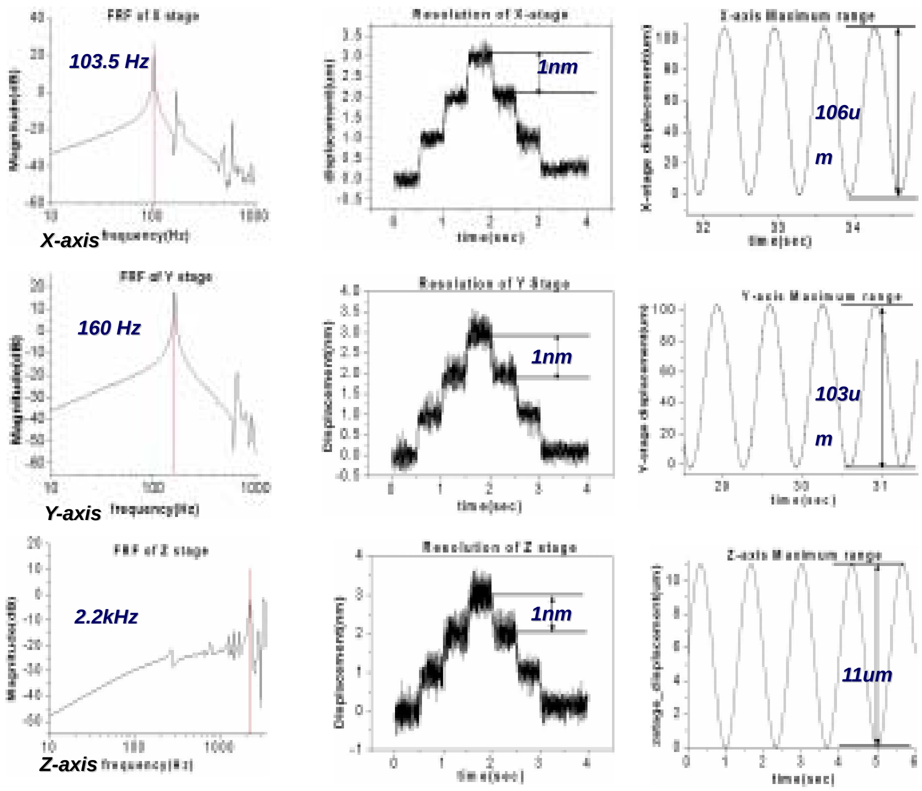


Fig. 7(a) Fig. 7(b) Fig. 7(c)

Fig. 7 Experimental results :

a) 1st natural frequency of XYZ stage b) step response c) maximum range of XYZ stage

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[1] Jae W. Ryu, "Optimal design of flexure hinge based xytheta wafer stage”, Precision Engineering, 1997, v21 no.1, pp.18 - 28