Specific geometries of resonant cantilevers for Scanning Force Microscopy

Julian Le Rouzic, Bernard Cretin, Pascal Vairac, and Bruno Cavallier
FEMTO-ST Institute
Besançon, France
Email: julian.lerouzic@femto-st.fr

***Abstract*— In this paper, specific geometries of resonant cantilevers for scanning force microscopy aimed to reduce sliding between tip and sample have been presented. These cantilevers have been designed for the scanning microdeformation microscope. Flexural and torsional vibration modes have been observed and compared to finite element simulations. Static deflections and dynamic sliding have been studied and the results have confirmed the efficiency of the cantilevers to keep the tip vertical during contact and to reduce the displacement of the tip on the surface.**

I. INTRODUCTION

One of the major issues in scanning force microscopy is the application of tangential forces between the tip and the sample during contact. Actually when tangential force becomes too high, the tip slides on the surface (Fig. 1). This leads to prevent a good localization of the measurement and to limit the quantification of the local contact stiffness.

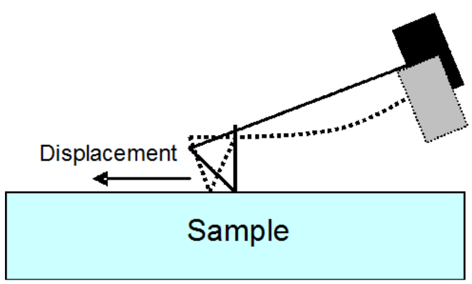

Fig. 1. Illustration of the sliding of the tip on the surface during contact.

In atomic force microscopy, stick & slip can occur. The tip alternately sticks and slides on the surface when the force is too high. In dynamic mode, non linearities can appear in the contact resonance curves indicating a loss of contact stiffness, for example in lateral force microscopy [1].

In this paper, sliding occuring with classic rectangular cantilevers in the scanning microdeformation microscope has been shown. Actually a decrease of resonance contact frequency has been observed with an increasing excitation voltage. New resonant cantilevers using a simple mechanical principle to compensate the tip torsion have been proposed. A W-shape has been choiced. The cantilevers have been conceived with ANSYS software. The experimental static deflections have been observed and compared to those obtained with classic cantilevers. Flexural and torsional modes have been measured and have shown good agreement with ANSYS and LS-DYNA simulations. And finally we have exhibited the effective decrease of dynamic sliding thanks to contact resonance curves.

II. PRESENTATION OF THE SCANNING MICRODEFORMATION MICROSCOPE

The scanning microdeformation microscope (SMM) is a type of AC-force contact microscope developped at FEMTO-ST institute [2]. The sensor is a micromechanical resonator, ordinarily composed of a silicon rectangular cantilever with a small sharp sapphire tip at the end. The cantilever is glued onto a piezoelectric bimorph transducer at the other end. The transducer excites the vibration of the tip-sample system. The tip remains in contact with the sample and vibrates at some kHz with an amplitude of some nanometres. Amplitude and phase of the vibrating cantilever are measured with a high sensitivity heterodyne interferometer [3,4]. The operation of the SMM is described in Fig. 2.

The signal at the probe output is averaged with the double-phase lock-in amplifier. Amplitude and phase of the cantilever displacement are recorded by the computer. Moreover, a modulated laser diode is used in a deflectometer to control the static force applied on the sample thanks to the second lock-in (and the third one can be used for a transmission mode operation). This microscope is an effective tool to record images of surfaces and subsurfaces with heterogeneous local elasticity or to characterize elastic properties of a material.

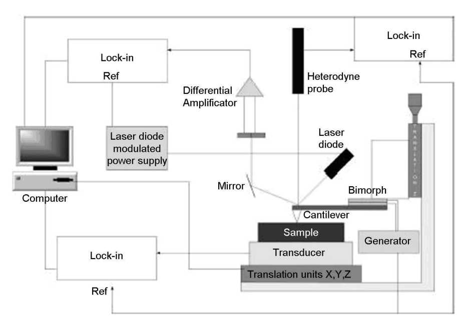

Fig. 2. Principle of the SMM.

The SMM enables to quantitatively measure the Young's modulus. The tip is put in contact with the sample and an additional static force is applied by vertically displacing the clamped end of the cantilever. Then the excitation frequency is scanned. The resonant frequency depends on the static force applied via the contact stiffness. Actually, by measuring this resonant frequency, the local contact stiffness can be estimated and then, with a well-suited model, the local Young's modulus. Other ultrasonic non-invasive methods like atomic force acoustic microscope (AFAM), ultrasonic force microscopy (UFM) or AFM spectroscopy with heterodyne interferometer can make such a characterization on the nanometre scale but with less accuracy because the contact model must take into account additional forces on this scale [5-9].

III. Sliding on the Scanning Microdeformation Microscope

With a classic rectangular cantilever, dynamic sliding can be observed on the contact resonance curves. Actually when excitation voltage V_{exc} becomes too high, non linearities appears. Fig. 3 shows the contact resonance curves obtained on a silicon surface for an increasing excitation voltage. The curves are asymetric. The amplitude of vibration doesn't increase linearly with the excitation and the resonance frequency decreases (Fig. 4). It can be explained by the loss of lateral contact stiffness due to sliding.

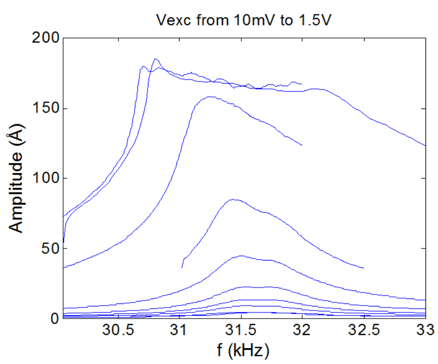

Fig. 3. Resonance curves obtained with a classic cantilever in contact with a silicon surface, for a static force of 1.5 mN, for excitation voltages from 10 mV to 1.5 V.

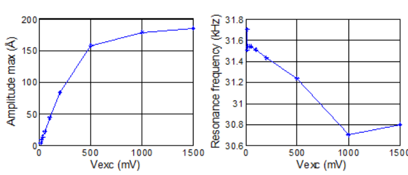

Fig. 4. Evolution of the amplitude of vibration and the resonant frequency as a function of the excitation voltage for the curves of Fig. 3.

Sliding can be reduced by increasing the static force applied and by using a stiffer cantilever but still occurs for a bit higher amplitude of vibration. The underestimation of the contact stiffness leads to limit the quantification of the local elastic constants. So we have thought to specific geometries of resonant cantilevers to prevent the tip from sliding on the surface.

IV. Specific Geometries of Resonant Cantilevers

A. Conception

A W-shaped cantilever has been imagined, using a simple mechanism of correction, to keep the tip vertical during contact (Fig. 5). The tip is located on the center of the cantilever. Actually by choosing an appropriate ration between the lengths l_1 and l_2, the two beams exactly compensate the flexion of the cantilever.

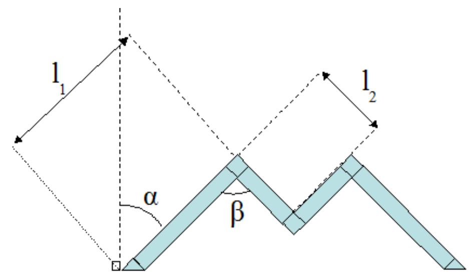

Fig. 5. Scheme of the geometry of the new cantilevers conceived.

The conception has been realized thanks to ANSYS software. A parametric study has been made. The thickness of the cantilevers and the width of the beams have been kept constant (respectively 150 μm and 400 μm). The other parameters have been modified and the tip torsion and the stiffness of the cantilever have been recorded. This has enabled us to choose 10 different geometries optimized to prevent sliding and with stiffnesses from 500 N/m to 150000 N/m (Fig. 6). Different stiffnesses have been chosen to optimize the sensitivity to the local contact stiffness depending on the material thanks to a precedent study [10].

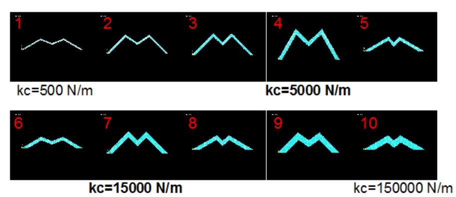

Fig. 6. Geometries of the 10 W-shaped cantilevers conceived with ANSYS.

The cantilevers have been fabricated with KOH attack and DRIE process. It has enabled us to obtain satisfying vertical sides (Fig. 7).

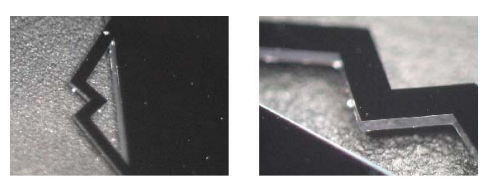

Fig. 7. Photography of one of the fabricated W-shaped cantilevers.

B. Characterization

1) Static deflections: The static deflections of two W-shaped cantilevers (W4 and W7) have been measured on a silicon surface thanks to the deflectometer and we have compared them to those obtained wtih a classic cantilever (Fig. 8). Actually W-shaped cantilevers have shown deflections 10 to 20 times lower than the classic ones, indicating that the tip remains almost vertical during contact. It can be assumed that the displacement of the tip on the surface has been reduced.

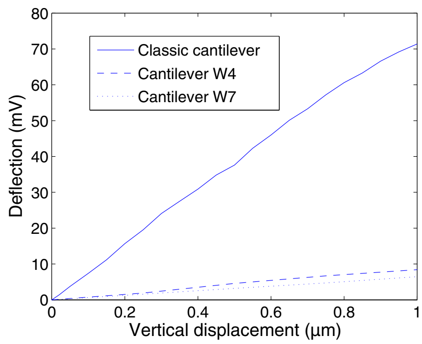

Fig. 8. Static deflections measured for two W-shaped cantilevers and for a classic one on a silicon surface.

Finite element simulations have confirmed these measurements. The software LS-DYNA has been used, which is a solver using ANSYS meshings, so our meshings could be imported. The contact between a SMM tip and a surface has been studied, showing good agreement with experiments. The meshings are described in Fig. 9. Meshing becomes very accurate on the contact areas.

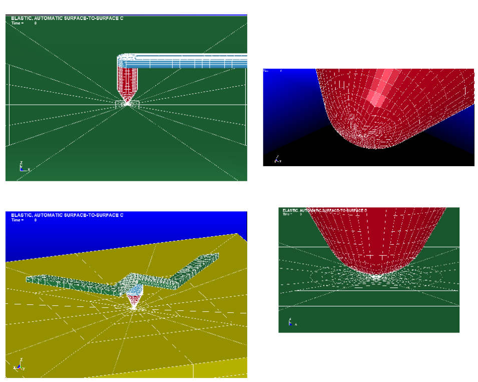

Fig. 9. Meshings used for LS-DYNA simulations.

LS-DYNA simulations have shown that while lateral displacement on the surface is important with a classic cantilever (120 nm for a static displacement of 1 μm on a silicon surface), it is 6 to 7 times lower with a W-shaped cantilever (Fig. 10). These simulations have confirmed the static satisfying behaviour of our new cantilevers. The tip remains vertical, so it is always the same area of the tip which is put in contact and the lateral displacement is very reduced enabling a good localization of the measurement.

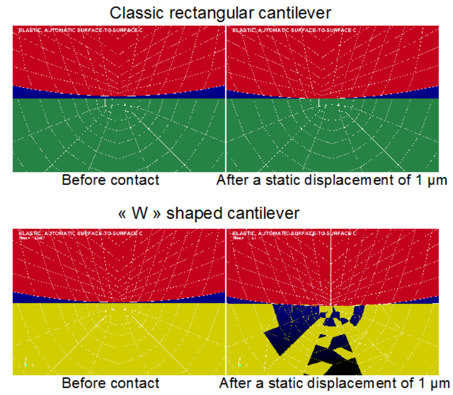

Fig. 10. LS-DYNA simulations of the sliding of the tip on the silicon surface, for a vertical static displacement of 1 μm, for a classical cantilever and for the W-shaped cantilever W7.

2) Vibration modes: The W-shaped cantilevers have been excited thanks to a piezoelectric ceramic. Free flexural and torsional vibration modes have been observed and compared to ANSYS simulations. The Fig. 11 gives for example the spectrum of the cantilever W4.

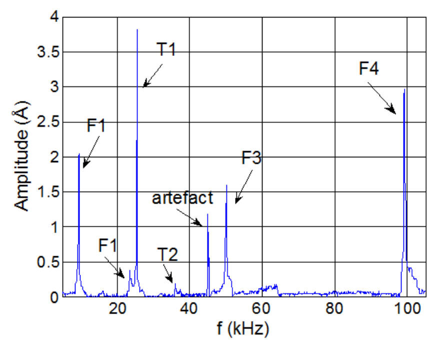

Fig. 11. Free amplitude of vibration (Å) of the cantilever W4 as a function of the frequency (kHz). Flexural and torsional modes can be observed.

TABLE I compares the experimental measured frequencies and the ANSYS computed ones. Flexural and torsional modes have easily been observed by the same excitation. A good agreement has been obtained for the first modes but less accuracy with higher modes.

TABLE I
FREE VIBRATION MODES OF THE W-SHAPED CANTILEVER W4.

Mode	Experimental frequency (Hz)	ANSYS computed frequency (Hz)
Flexion 1	9324	9705
Flexion 2	25325	24497
Torsion 1	25300	25579
Torsion 2	35928	41505
Flexion 3	50100	59873
Flexion 4	99200	82765

The contact modes have also been measured on silica and silicon surfaces. The best sensitivity has been obtained for the cantilever W7. The contact resonance curves can be seen in Fig. 12. A good frequency shift has been seen between the two materials. So it has been shown that these cantilevers enable mechanical characterization.

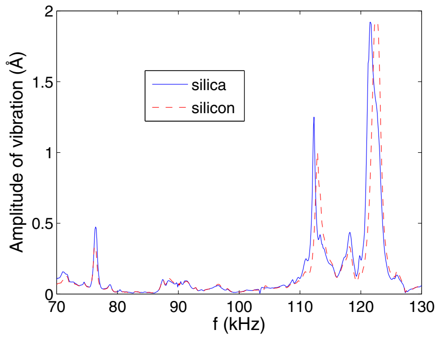

Fig. 12. Amplitude of vibration as a function of the frequency, on silicon and silica surfaces, for the W-shaped cantilever W7, for a static force of 7.5 mN.

An even much better sensitivity has also been observed for a higher static force, especially for the torsional modes (Fig. 13).

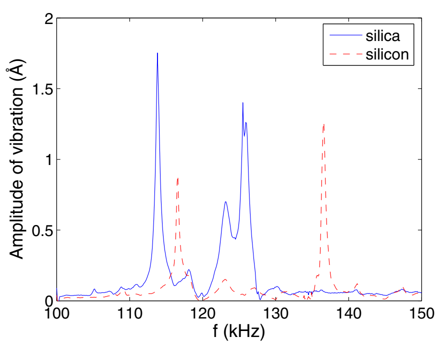

Fig. 13. Amplitude of vibration as a function of the frequency, on silicon and silica surfaces, for the W-shaped cantilever W7, for a static force of 15 mN.

ANSYS simulations have been done to fit the contact experimental frequencies but without obtaining satisfying results. So LS-DYNA simulations have been realized and have shown a good accuracy for the first flexural mode but far less for the following modes (TABLE II).

3) Dynamic sliding: Finally to verify the dynamic behaviour of the W-shaped cantilevers the contact resonance curves have been measured for an increasing excitation voltage (Fig. 14). It can be seen that the resonance curves for the flexural mode are quite symetric. The resonance frequency is constant even for high amplitudes of vibration. This means that dynamic sliding is reduced and it confirms the ability of the W-shaped cantilevers to prevent the tip from sliding on the surface during oscillations. But it can be observed that non

TABLE II

COMPARISON EXPERIMENT/LS-DYNA SIMULATIONS FOR THE VIBRATION MODES OF THE W-SHAPED CANTILEVER W7, IN CONTACT ON A SILICON SURFACE, FOR A STATIC FORCE OF 7.5 MN.

Mode	Experimental frequency (Hz)	LS-DYNA computed frequency (Hz)
Flexion 1	76400	72050
Torsion 1	112300	84714
Torsion 2	121550	90874

linearities appear on the torsional mode, which indicates that there is sliding. It is normal because the W-shaped cantilevers are designed to prevent the tip from sliding in the length direction but not from left to right.

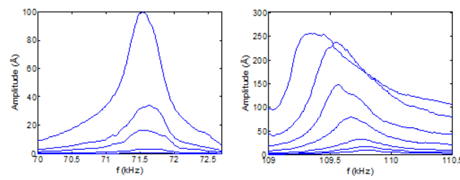

Fig. 14. Contact resonance curves on a silicon surface of the W-shaped cantilever W7, for a static force of 1.5 mN, for an increasing voltage. The flexural mode is on the left, while the torsional mode is on the right.

V. CONCLUSION

The efficiency of the W-shaped cantilevers to reduce sliding, both in static and dynamic behaviours, has been shown in this paper. These cantilevers have exhibited a good sensitivity enabling mechanical characterization. The contact behaviour modeling (requiring a numeric solving because of the complex shape) is quite delicate but has provided a good accuracy for the first mode.

ACKNOWLEDGMENT

The authors would like to thank the city of Besançon for supporting this project.

REFERENCES

[1] V. Scherer, W. Arnold, *Friction force microscopy at ultrasonic frequencies* In: B. Bhushan (ed.) Micro/nanotribology and its applications. Kluwer Academic, 1997.
[2] F. Sthal and B. Cretin, *Appl. Phys. Lett.* **62** 829, 1993.
[3] B. Cretin and P. Vairac, *Appl. Phys. Lett.* **71** 2082–4, 1997.
[4] P. Vairac and B. Cretin, *Opt. Commun.* **132** 19–23, 1996.
[5] U. Rabe and W. Arnold, *Appl. Phys. Lett.* **64** 1493–5, 1994.
[6] N. A. Burnham, A. Kulik, G. Gremaud , P. J. Gallo and F. Ouveley,*J. Vac. Sci. Technol.* B **14** 794–9,1996.
[7] O. Kolosov and K. Yamanaka, *Jpn. J. Appl. Phys.* **32** L1095–8, 1993.
[8] E Chilla, T. Hesjedal and H. J. Frohlich, *Proc. IEEE Ultrasonics Symposium* pp. 363–6, 1994.
[9] E. Dupas E, G. Gremaud G, A. Kulik and J. L. Loubet, *Rev. Sci. Instrum.* **72** 3891–7, 2001.
[10] J. Le Rouzic, P. Vairac, B. Cretin and P. Delobelle, *Rev. Sci. Instrum.* **79** 033707, 2008.