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Step Modelling of a High Precision 2DoF (Linear-Angular) Microsystem

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***Abstract*— In this paper, a new type of microsystem is presented : a system able to perform linear and angular motion. First, the microactuator used is studied. An approximation of the working equations is proposed in accordance with Finite-Element simulation. The microactuator used is inserted in the microsystem and a separated modelling of the whole system in linear and in angular motion is given. *Stick* and *skid* phases of each motion are independently studied.**

***Index Terms*— Step modelling, piezoelectric microactuators, linear-angular motion.**

I. Introduction

Similar to *Inch-Worm*, *Stick-Slip* becomes a principle more and more used in systems working in the microworld. It is specially used for micropositioning [1][2][3][4]. That is mainly due to the high precision and the high range that it offers. On the other hand, the need in micropositioning has increased in multi degrees of freedom (dof) since some years. Even though 1dof microsystems always stays the basic application, planar, spatial or linear angular manipulations become more and more frequent. Solutions may be brought out in combining several different microactuators in the same system but this way is sometimes unsuitable. The realization of such systems is effectively difficult and the resulting imprecision is sometimes inadequate : geometric imprecision of the microsystem increases with the number of its microcomponents.

Ref.[5] has proposed a new configuration of piezoelectric microactuator allowing a microsystem have easily more dof in *stick-slip* functioning with a submicrometric precision. In fact, a microactuator may possess more than 1 dof and it is possible to make several microactuators within the same bulk material.

On the other hand, as part of the *Flexible Microassembly Station* project [6][7], a microsystem with a wide range, high precision and able to have a linear and an angular motion is needed (Fig. 1). The final object is to realize a microfactory station. It seems that the microactuators proposed in [5] may correspond to the need. So, this paper develops a dynamical model of a step of our microsystem using them. In fact, each motion (angular and linear) is modeled separately. The obtained model will then facilitate the control of the whole system in large range and in precise manipulation of micro-object.

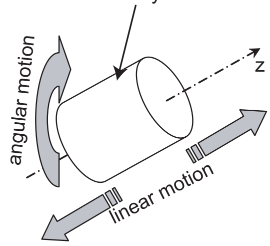

Fig. 1. Kinematical scheme of a microstation :a microsystem can rotate around Oz axis and move along it.

First, the microactuator is presented. The working equations are given. After that, the microsystem is presented. Each phase (*stick* and *slip*) of each motion (linear and angular) is separately modeled and finally, the results of simulations are discussed.

II. Presentation of the microactuator

A. Principle

The Fig. 2 represent the microactuator used. The examples of application presented in [5] use the transversal displacement $\delta x = f_1(d31)$ and minimize the displacement due to the rotation $\phi = f_2(d33)$ (Fig. 2-b). The final displacement, a step, would be then : $\Delta x = \delta x + r_s \cdot \phi$

where r_s indicates the radius of the end-effector and $\delta x \cdot \phi < 0$.

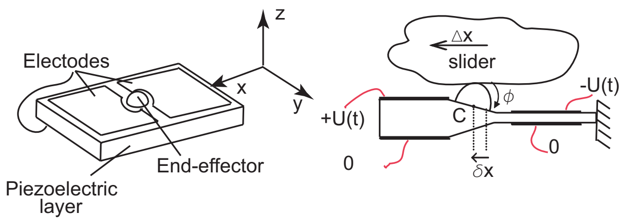

Fig. 2. Principle of the microactuator.

B. Application

It can be demonstrated that according to the mechanical boundaries and to the configuration of the whole system, the displacement from the angle ϕ may be also profited. Let us consider the configuration shown in (Fig. 3) and apply electrical potentials (U and $-U$).

Due to the presence of the alumina which behaves like an embedding, the value of δx becomes dependent of the considered point of the piezoelectric layer when covering the 0z axis :

$$\overrightarrow{grad}(\delta x(x, y, z)) \cdot \vec{k} \neq 0 \tag{1}$$

Where $\vec{k}$ is the 0z unit vector.

We focus on the displacement δx_C relative to the point C which is the inertia center of the end-effector (half of sphere). We assume that the distance g of C from the top of the hemishere is nearly equal to the radius r_s of it (Fig. 4). The Fig. 5-a shows the result using the Finite-Element-Method (FEM, ANSYS). From that, an approximation of the deformed shape is proposed (Fig. 5-b).

We introduce a scalar field named ζ_{31} correcting the piezoelectric equation in order to give the more approached displacement field. According to the approximation above, ζ_{31} depends linearly on z but stays unchanged whatever U is. If $\zeta_{31}(C) = q_{31}$, the 0x displacement of C becomes :

$$a_1 \cdot \ddot{\delta x}_C + b_1 \cdot \dot{\delta x}_C + \delta x_C = q_{31} \cdot (d_{31} \cdot U + e \cdot s_{13} \cdot \sigma) \tag{2}$$

where σ is the mechanical stress applied to the piezoelectric layer, e the thickness of the layer, d_{31} the transversal charge constant and s_{13} the transversal elastic constant. We assume that the piezoelectric layer has a second order dynamic. So, the coefficients a_1 and b_1 respectively represent inertial and viscous parts of the piezoelectric layer deformation when considering the transversal effect.

Let $\vec{F_e}$ the applied equivalent force to warp the piezoelectric plate. Its distance from C is equal to the equivalent radius r_a (Fig. 5-b). This force is transmitted to the end-effector as a couple Γ (Fig. 6) described by :

$$\Gamma = 2 \cdot r_i \cdot F_e \cdot \cos(\phi) \tag{3}$$

With r_i the internal radius of an electrode.

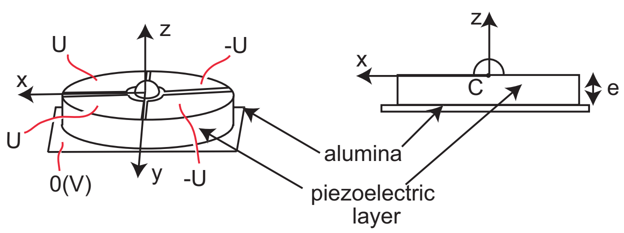

Fig. 3. Configuration of the electrodes for 2DoF.

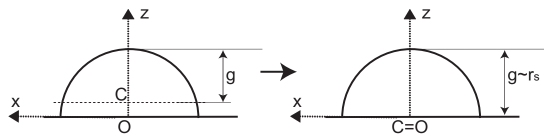

Fig. 4. The distance g of C from the top is supposed equal to the radius.

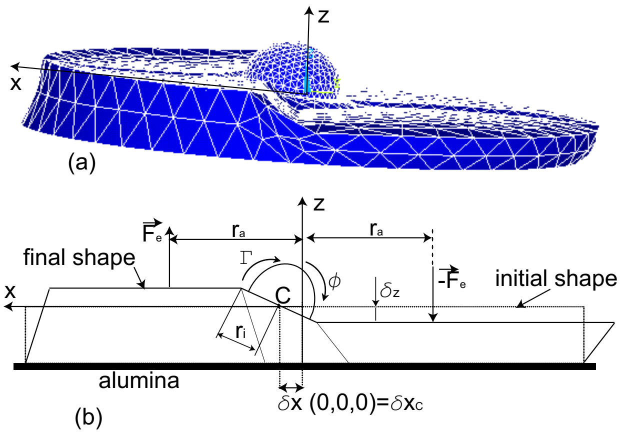

Fig. 5. Functioning of the microactuator. a : result of simulation using Finite-Element-Method. b : simplified scheme in Oxz plan.

The stress is then given by :

$$\sigma = \frac{F_e}{S} \tag{4}$$

Where S represents the surface of two electrodes.

In that way the first equation of the microactuator is the following :

$$a_1 \cdot \ddot{\delta x}_C + b_1 \cdot \dot{\delta x}_C + \delta x_C = q_{31} \cdot \left(d_{31} \cdot U + \frac{e.s_{13}}{2 \cdot r_i \cdot S \cdot \cos(\phi)} \cdot \Gamma\right) \tag{5}$$

On the other hand, it is assumed that the ϕ angle can be written as :

$$\sin(\phi) = \frac{\delta_z}{r_i} \tag{6}$$

$$a_2 \cdot \ddot{\delta z} + b_2 \cdot \dot{\delta z} + \delta z = q_{33} \cdot (d_{33} \cdot U + e \cdot s_{11} \cdot \sigma) \tag{7}$$

Where δz is the axial displacement of the surface of the electrodes (Fig. 5), a_2 and b_2 respectively represent the inertial and the viscous parts of the piezoelectric layer deformation when considering the axial effect. Here, d_{33} and s_{11} respectively represent the axial charge constant and the transversal elastic constant

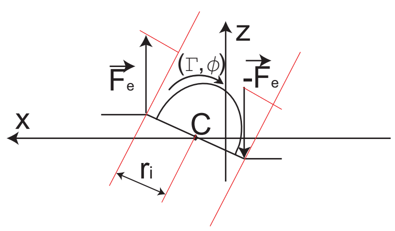

Fig. 6. Representation of the equivalent radius r_a.

Here, we have introduced a second corrector named q_{33} having as function the relation between the piezoelectric equation and the real displacement of C (Fig. 5-b).

Thus the second equation of the microactuator is :

$$(1 - a_2) \cdot \sin(\phi) + b_2 \cdot \cos(\phi) = \frac{q_{33}}{r_i} \cdot \left(d_{33} \cdot U + \frac{e \cdot s_{11}}{2 \cdot r_i \cdot S \cdot \cos(\phi)} \cdot \Gamma\right) \tag{8}$$

III. MICROACTUATOR IN CONTACT WITH A BASE

Let us put the microactuator on a base and apply a constant vertical load $\overrightarrow{N}$ on it (Fig. 7-a). We assume that the contact at I is punctual. The influences of $\overrightarrow{N}$ on the strain of the piezoelectric layer are inside the correctors q_{31} and q_{33}. These coefficients may be determined by simulation with ANSYS.

Applying symmetrically and slowly a voltage to the electrodes, we obtain a rolling without sliding of the hemisphere : *stick*-phase. A displacement Δx of C is got (Fig. 7-b) :

$$\Delta x = r_s \cdot \phi \tag{9}$$

According to (5), the alumina has a relative displacement in relation with C . It has then a small absolute displacement in this phase :

$$x_{alu} = r_s \cdot \phi + \delta x_C \tag{10}$$

with $\phi \cdot \delta x_c < 0$

We apply now an abrupt slope of electric potential (Fig. 7-c). The static friction is quickly exceeded and the hemisphere skids. The alumina tries to catch the difference δx_C relative to C and a step Δ_x will be achieved. We propose to call this functioning *stick-skid*. In fact, unlike the *slip*, the point C of the *skid*-phase has not a motion.

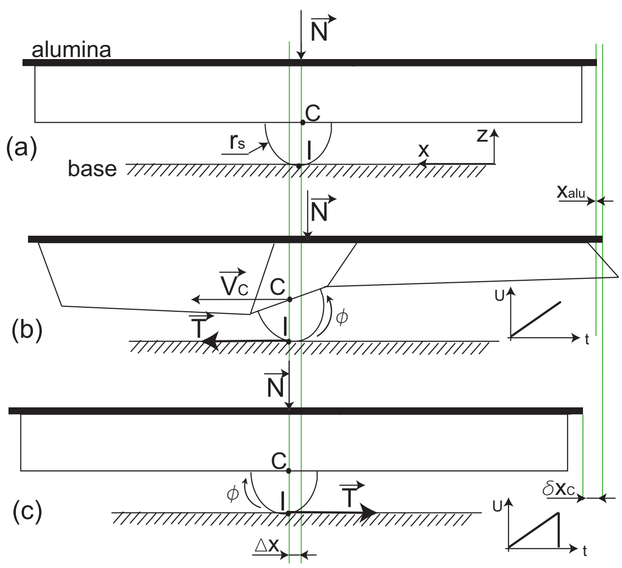

Fig. 7. a : the microactuator placed on a base. b : rolling without sliding of the end-effector (hemisphere). c : skid of the end-effector.

The friction law is modeled using the LuGre dynamic model [8]. In fact, many nearest applications use the model : from *stick-slip* to *dynamic of tires analysis*. With the standard parameters, the governing equations are :

$$T = N \cdot (\sigma_0 \cdot a + \sigma_1 \cdot \dot{a} + \sigma_2 \cdot V_I) \tag{11}$$

$$\dot{a} = V_I - \frac{\sigma_0 \cdot |V_I|}{g(V_I)} \cdot a \tag{12}$$

$$g(V_I) = \mu_c + (\mu_s - \mu_c) \cdot e^{-\left|V_I/V_s\right|^2} \tag{13}$$

Where constants σ_0, σ_1 and σ_2 respectively represent the normalized rubber longitudinal lumped stiffness, the normalized rubber longitudinal lumped damping and the normalized viscous relative damping. Constants μ_c indicates the normalized Coulomb friction and μ_s the normalized static one. The internal friction state is given by a. V_I is the relative velocity at I and V_s the Stribeck relative velocity.

IV. THE LINEAR-ANGULAR STEPPING MICROSYSTEM

We now use the microactuator in order to move a mobile having two operational degrees of displacement (dod). Two end-effectors are necessary in order to have static mechanism (Fig. 8-a). The realization of the microactuators is done by J.M. Breguet's team in Swiss Federal Institute of Technology Lausanne (EPFL). Three pair of microactuator spread out 360° are used (Fig. 8-b) to support the microsystem. Placed on a spindle, the whole system can move along 0x axis and rotate around it (Fig. 8-c) step by step. Of course, according to the considered reference, either the spindle (the system is a *linear-angular stepping micromotor*) or the microsystem (the system is a *linear-angular stepping microsystem*) moves.

A. *Principal assumptions*

– The study of the microsystem may be reduced to the study of a microactuator motion (Fig. 9),
– the referential associated to the spindle is supposed to be a Galilean one,
– a normal radial force $\overrightarrow{N}$ is applied for each microactuator. It has a modulable intensity and the weight of the microsystem is neglectible in relation with the whole of the radial forces,
– the base (spindle) and the hemisphere are assumed to be rigid, the radial vibrations due to their deformations are then neglected,
– the contact between the hemisphere and the spindle is punctual and adhesion forces between them are neglectible,
– neglecting the displacement δ_z of C, its motion when the microsystem moves along 0x stays a straight. On the other hand, when this last does a rotation around the spindle, C has a circular trajectory.

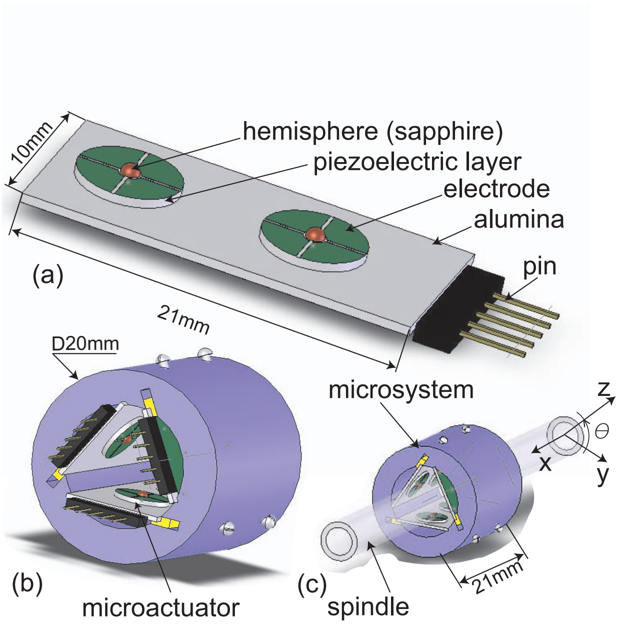

Fig. 8. a : two actuated end-effectors on an alumina plate. b : three plate of alumina spread out 360° for the microsystem. c : the microsystem has two DoF.

B. Modelling of a rotation step

Let us analyse the dynamic of the hemisphere which revolves around the spindle (Fig. 10) with a R radius.

From dynamic laws, we can write :

$$J_C \cdot \left(\ddot{\phi} + \ddot{\theta}\right) = \Gamma_m - r_s \cdot T \tag{14}$$

$$J_0 \cdot \ddot{\theta} = R \cdot T \tag{15}$$

Where J_C and J_O respectively represent the inertial moment of the hemisphere in relation with C and with the reference origin O.

Γ_m is the torque applied to the hemisphere so that :

$$\Gamma_m = -\Gamma \tag{16}$$

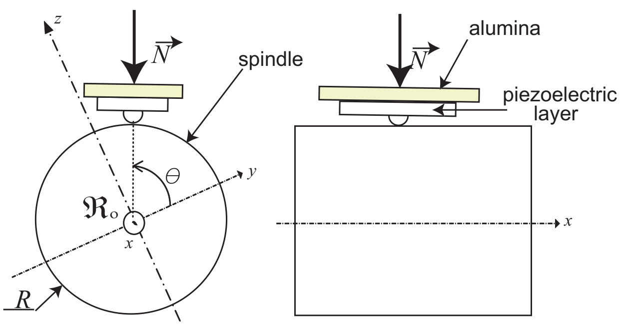

Fig. 9. Simplified scheme to study the motions of the microsystem.

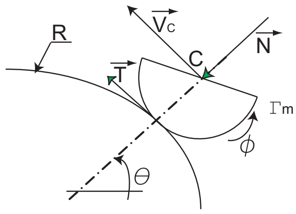

Fig. 10. Study of the hemisphere in rotation mode.

1) stick-phase: While the motion is rolling without sliding, it is deduced from kinematic that :

$$\ddot{\theta} = \frac{r_s}{R} \cdot \ddot{\phi} \tag{17}$$

Using the dynamic equations (14) and (15), inputting the static one (16), we obtain :

$$\Gamma = -J_{equ} \cdot \ddot{\phi} \tag{18}$$

With

$$J_{equ} = \frac{J_O \cdot r_s^2 + J_C \cdot R \cdot (R + r_s)}{R^2} \tag{19}$$

Taking equation (18) and considering the piezoelectric working equations (5) and (8), state equations of the hemisphere are :

$$\frac{d\phi}{dt} = \dot{\phi} \tag{20}$$

$$\frac{d\dot{\phi}}{dt} = \frac{2 \cdot r_i \cdot S \cdot \cos(\phi)}{J_{equ} \cdot e \cdot s_{11}} \cdot \Big(d_{33} \cdot U - \frac{r_i}{q_{33}} \cdot \big((1 - a_2) \cdot \sin(\phi) + b_2 \cdot \cos(\phi)\big)\Big) \tag{21}$$

$$\frac{d\delta x_C}{dt} = \dot{\delta x}_C \tag{22}$$

$$\frac{d\dot{\delta x}_C}{dt} = \frac{q_{31}}{a_1} \cdot \left(d_{31} - \frac{s_{13}}{s_{11}} \cdot d_{33}\right) \cdot U + \frac{s_{13} \cdot q_{31} \cdot r_i}{s_{11} \cdot q_{33} \cdot a_1} \cdot \big((1 - a_2) \cdot \sin(\phi) + b_2 \cdot \cos(\phi)\big) - \frac{b_1}{a_1} \cdot \dot{\delta x}_C - \frac{\delta x_C}{a_1} \tag{23}$$

In order to check if there is no sliding during rolling, the value of T must be known. It can be got from (15), (17) and (21). The first output equation of the rotation *stick*-phase is then :

$$T = \frac{2 \cdot J_O \cdot r_s \cdot r_i \cdot S \cdot \cos(\phi)}{J_{equ} \cdot R \cdot e \cdot s_{11}} \cdot \Big(d_{33} \cdot U - \frac{r_i}{q_{33}} \cdot \big((1 - a_2) \cdot \sin(\phi) + b_2 \cdot \cos(\phi)\big)\Big) \tag{24}$$

On the other hand, the dynamic in rotation of the microsystem is wanted. It means that equation associated with alumina must be found as it is joined to the microsystem. In *stick* phase rotation, the alumina equation equivalent to (10) may be written as :

$$\theta_{alu} = \frac{r_s}{R} \cdot \phi + arctg\left(\frac{\delta x_C}{(R + r_s + e)}\right) \tag{25}$$

The equation (25) is then the second output equation of our system in stick *phase* of the rotation mode.

2) skid-phase: The absolute velocity of C is null but a relative velocity V_I exists in the contact. From kinematic laws :

$$V_I = r_s \cdot \dot{\phi} \tag{26}$$

and

$$\theta = \dot{\theta} = \ddot{\theta} = 0 \tag{27}$$

Using the dynamic equation (14) and (15), the kinematic expressions (26) and (27) and the static one (16), we have :

$$J_C \cdot \ddot{\phi} = -\Gamma - r_s \cdot T \tag{28}$$

From (28), using the piezoelectric working equations (5) and (8) and taking into account the friction model (11), (12) and (13), the dynamic model of the hemisphere is :

$$\frac{d\phi}{dt} = \dot{\phi} \tag{29}$$

$$\begin{aligned} \frac{d\dot{\phi}}{dt} = \frac{1}{J_C} \cdot \Bigg[& \frac{2 \cdot r_i \cdot S \cdot \cos(\phi)}{e \cdot s_{11}} \cdot \Big(d_{33} \cdot U \\ & - \frac{r_i}{q_{33}} \cdot ((1 - a_2) \cdot \sin(\phi) + b_2 \cdot \cos(\phi)) \Big) \\ & - r_s \cdot N \cdot \Big(\sigma_0 \cdot a + (\sigma_1 + \sigma_2) \cdot r_s \cdot \dot{\phi} \\ & - \frac{\sigma_0 \cdot \sigma_1 \cdot a \cdot \left| r_s \cdot \dot{\phi} \right|}{\left(\mu_c + (\mu_s - \mu_c) \cdot e^{-\left| r_s \cdot \dot{\phi} / V_s \right|^2} \right)} \Big) \Bigg] \end{aligned} \tag{30}$$

$$\frac{da}{dt} = r_s \cdot \dot{\phi} - \frac{\sigma_0 \cdot \left| r_s \cdot \dot{\phi} \right| \cdot a}{\left(\mu_c + (\mu_s - \mu_c) \cdot e^{-\left| r_s \cdot \dot{\phi} / V_s \right|^2} \right)} \tag{31}$$

$$\frac{d\delta x_C}{dt} = \dot{\delta} x_C \tag{32}$$

$$\begin{aligned} \frac{d\dot{\delta} x_C}{dt} = & \frac{q_{31}}{a_1} \cdot \left(d_{31} - \frac{s_{13}}{s_{11}} \cdot d_{33} \right) \cdot U \\ & + \frac{s_{13} \cdot q_{31} \cdot r_i}{s_{11} \cdot q_{33} \cdot a_1} \cdot ((1 - a_2) \cdot \sin(\phi) + b_2 \cdot \cos(\phi)) \\ & - \frac{b_1}{a_1} \cdot \dot{\delta} x_C - \frac{\delta x_C}{a_1} \end{aligned} \tag{33}$$

The first output equation must be the friction T which let us check the skid phase :

$$\begin{aligned} T = N \cdot \Big(& \sigma_0 \cdot a + (\sigma_1 + \sigma_2) \cdot r_s \cdot \dot{\phi} \\ & - \frac{\sigma_0 \cdot \sigma_1 \cdot a \cdot \left| r_s \cdot \dot{\phi} \right|}{\left(\mu_c + (\mu_s - \mu_c) \cdot e^{-\left| r_s \cdot \dot{\phi} / V_s \right|^2} \right)} \Big) \end{aligned} \tag{34}$$

In spite of the zero rotation of C according to (27), the alumina executes a rotation θ_{alu} in skid phase. The second output equation in *skid* phase is then :

$$\theta_{alu} = arctg \left(\frac{\delta x_C}{(R + r_s + e)} \right) \tag{35}$$

C. Modelling of a linear motion step

The Fig. 11 below show the hemisphere in linear motion :

Dynamic laws let us obtain the dynamic equations system of the hemisphere :

$$J_C \cdot \ddot{\phi} = \Gamma_m - r_s \cdot T \tag{36}$$

$$m \cdot \gamma_C = T \tag{37}$$

where m indicates the mass of the hemisphere and $\gamma_C = dV_C/dt$ the acceleration of C.

1) stick-phase: From kinematic laws, we deduce :

$$V_C = r_s \cdot \dot{\phi} \tag{38}$$

We can then write :

$$T = m \cdot r_s \cdot \ddot{\phi} \tag{39}$$

From the dynamic equations (36) and (37), using the kinematic term (39) and inputting the static equivalence (16), we obtain the following equation :

$$\ddot{\phi} \cdot \left(J_C + m \cdot r_s^2 \right) = -\Gamma \tag{40}$$

To obtain the state equations of the hemisphere, we use equation (40) and the two piezoelectric equations (5) and (8) :

$$\frac{d\phi}{dt} = \dot{\phi} \tag{41}$$

$$\begin{aligned} \frac{d\dot{\phi}}{dt} = & \frac{2 \cdot r_i \cdot S \cdot \cos(\phi)}{(J_C + m \cdot r_s^2) \cdot e \cdot s_{11}} \cdot \Big(d_{33} \cdot U - \\ & \frac{r_i}{q_{33}} ((1 - a_2) \cdot \sin(\phi) + b_2 \cdot \cos(\phi)) \Big) \end{aligned} \tag{42}$$

$$\frac{d\delta x_C}{dt} = \dot{\delta} x_C \tag{43}$$

$$\begin{aligned} \frac{d\dot{\delta} x_C}{dt} = & \frac{q_{31}}{a_1} \cdot \left(d_{31} - \frac{s_{13}}{s_{11}} \cdot d_{33} \right) \cdot U \\ & + \frac{s_{13} \cdot q_{31} \cdot r_i}{s_{11} \cdot q_{33} \cdot a_1} \cdot ((1 - a_2) \cdot \sin(\phi) + b_2 \cdot \cos(\phi)) \\ & - \frac{b_1}{a_1} \cdot \dot{\delta} x_C - \frac{\delta x_C}{a_1} \end{aligned} \tag{44}$$

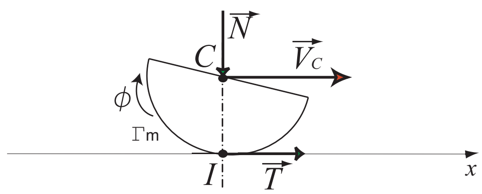

Fig. 11. The hemisphere in linear motion mode.

Like in rotation mode, the friction T is the first output variable interesting us. It is easily obtained with (39) and (42) :

$$T = \frac{2 \cdot m \cdot r_s \cdot r_i \cdot S \cdot \cos(\phi)}{(J_C + m \cdot r_s^2) \cdot e \cdot s_{11}} \cdot \Big(d_{33} \cdot U - \frac{r_i}{q_{33}} \cdot ((1 - a_2) \cdot \sin(\phi) + b_2 \cdot \cos(\phi))\Big) \quad (45)$$

The equation of the alumina (which is also the one of the microsystem) is directly obtained with (10). So, the displacement in *stick* phase is :

$$x_{alu} = r_s \cdot \phi + \delta x_C \quad (46)$$

2) skid-phase: Skid phase means that motion of C is null when the hemisphere turns around its inertial principal axis. Then, the curvature of the base doesn't affect the skid phase. So, we assume that equation of the friction T in *skid* phase of rotation is the same than the translation one. However, the displacement of the alumina in this phase is :

$$x_{alu} = \delta x_C \quad (47)$$

V. Simulation

The fig. Fig. 12 summarizes systemically the microsystem. The state equations were given by the dynamic of the piezoelectric layer (electromechanical states) and the hemisphere (mechanical states) (Fig. 12-a). The displacement of the microsystem is relative to the alumina.

The coefficient a_1, b_1,a_2 and b_2 which determine the dynamic of the piezoelectric layer are being identified. Then, our first step is to implement in MATLAB-SIMULINK the model with a quasi-static piezoelectric microactuator ($a_1 = b_1 = a_2 = b_2 = 0$). To insure the validity of that assumption, low working frequency were used.

We can also remark that if the input slope (dU/dt) is very high, sliding will certainly appear during rolling and the final step of the microsystem will be reduced. On the other hand, *skid* phase always generates vibration which sometimes contains high amplitude overpass (Fig. 13-a). Furthermore the *skid* phase is very delicate : the dynamic of the piezoelectric layer must not be neglected. We have therefore added a lull (duration = t_2) just after *skid*. In that case, before the *stick* reprise, the signals will have approximately been damped (Fig. 13-b).

The simulations were studied using PIC-151 piezoelectric layer with a thickness $e = 0.5mm$. In the simulation below (Fig. 14), working frequency is 9800Hz where the duration of the lull is ($t_2 = 20ns$) 1.96% of the the period one.

VI. Conclusion

A stick-skid based 2DoF microsystem was proposed. The piezoelectric microactuator equations which let it move were approximated. For each DoF (linear motion along Oz axis or angular motion around it), two dynamical models are necesary : the first one for the *stick* phase and the second one for the *skid*. The modelling combines the piezoelectric layer state equations and the hemisphere one and we use the LuGre model to express the friction. We have introduced a laps of time just after the *skid* phase so that vibrations are removed before the *stick* reprise.

This paper has presented the modelling of a step of the microsystem motions. Future work will consist on the realization of a prototype. In the *Flexible Microassembly Station* project, the use of several microsystems in cooperation (Fig. 15) is prominent so that complex tasks may be done using several microsystems.

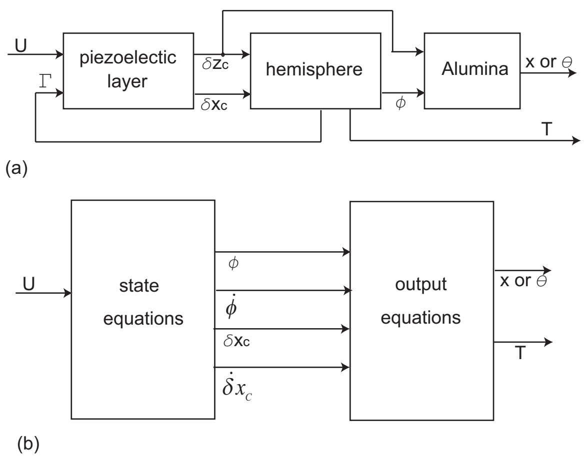

Fig. 12. a : systemic scheme representing the process of modelling. b : systemic global scheme.

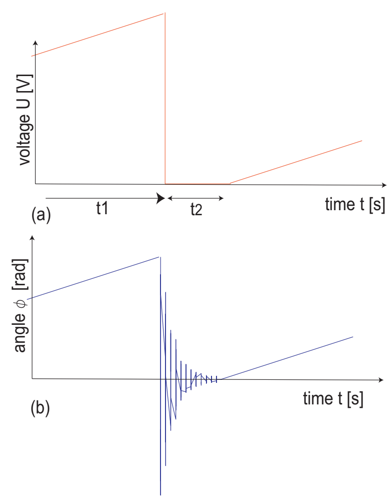

Fig. 13. a : introducing of a delay t_2 in *skid* phase. b : the *slip* phase restarts when vibrations are nearly damped.

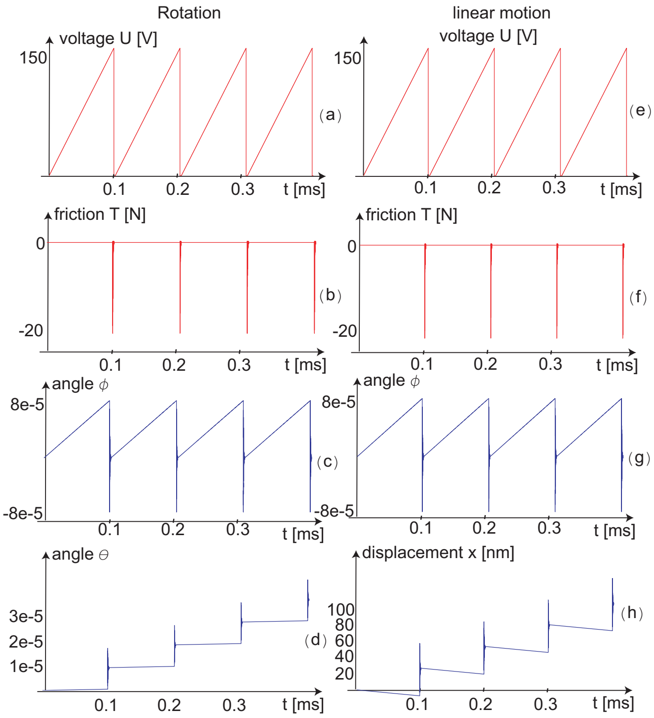

Fig. 14. Different results of simulation. a and e : applied voltage with frequency equal 9800Hz. b and f : evolution of the friction in angular and linear motion, during *stick*, its value is very low. c and g : evolution of the hemisphere rotation. e and h : evolution of the microsystem respectively in angular and linear motion.

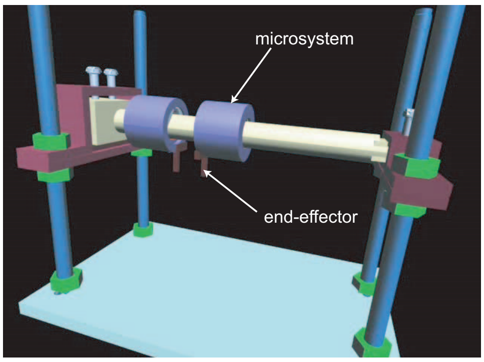

Fig. 15. When several microsystems are used, complex tasks may be done. Here, two microsystems are used in order to process *pick-and-place* task. The figure represents the principle of the future microstation studied in *Flexible Microfactory Project*.

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