

Modeling and simulating the stick-slip motion of the μ Walker, a MEMS-based device for μ SPAM¹

M. PATRASCU

S. STRAMIGIOLI

*Department of Control Engineering, Faculty of Electrical Engineering,
University of Twente, P.O. Box 217, 7500AE Enschede, The Netherlands*

M.Patrascu@el.utwente.nl

+31 53 489 2707

+31 53 489 2223

¹ μ SPAM stands for Micro Scanning Probe Array Memory

Abstract

In this paper, the accent is on modeling the stick-slip phenomenon of micro devices, where a case shall be presented from the field of scanning probe micro-actuators. The case is about the μ Walker, an electrostatic stepper motor which can deliver forces up to 1.7mN and has ranges up to 140 μ m. For the sake of a reliable operation, it is very important to control the stick-slip effects at the sliding surfaces.

In order to introduce the stick-slip effect, a basic model of a mass, spring and sliding surface is presented, accompanied by simulation results.

The total model of the device is then shown, again stressing the stick-slip phenomenon at the two sliding surfaces.

Simulations from the model presented fit the measurements and can also predict step sizes as a function of varying inputs. Using a model for predictions is very attractive when looking for a way to decrease development cost and time.

1. Introduction

One of the necessary components in probe array memory storage devices is an actuator that aligns and moves the probes with respect to the medium in order to be able to read and write data. In the μ SPAM project [1], the desired working speed should be above 10 mm/s in order to achieve access times below 10 ms and the precision, or tracking error, should not exceed 10 nm in order to enable densities up to 1 Tbit/in². The tracking function is being performed by an inchworm device (Figure 1), from hereon called the μ Walker. This device is also known in literature as the shuffle motor and has been developed by E. Sarajlic at the TST Group, at our University [2]. The μ Walker has a very high force density, in the order of 5 mN/mm²V², and the walking range extends beyond 100 μ m. In the present design, it can deliver forces greater than 1 mN, which make it very suitable for probe recording purposes. High forces are needed because in order to position certain components very fast, high acceleration and thus high forces are needed, which can generate the acceleration. Moreover in our design, the forces

generated must compensate for slip friction while moving at constant velocity and must be sufficiently high in order for the sliding surfaces to proceed from the stick to the slip state in a very short time.

Concerning stick-slip in a MEMS context, several literature references [3] present a derivation from the macroscopic friction models, like the brush model [4] and the well-known stiction/friction models presented in [5] and [6]. Remarkably, certain references [7], [8], [9] which treat subjects very much related to stick-slip do not present a model for this phenomenon, but instead treat it as a black box or even attempt to ignore it by adding a suitable controller. Definitely one of the most complete literature sources for micro- and nano-tribology can be found in [10].

After having introduced the actuation method for the μ Walker and the simulation package, stick-slip will be presented in Section 4 by means of a hypothetical example of a sliding mass attached to a spring. Section 5 presents the complete physical model of the micro stepper, followed by device optimization and parameter sweeping in Section 6.

Figure 1

2. μ Walker walking principle

Figure 2

In order to better understand how the μ Walker actually walks, the moving principle shall be described in the following. Figure 2 is a sketch of this process, where the sequence of six actuation signals on each of the two clamps and on the shuffle plate leads to one step to the left.

The moving cycle starts by applying a voltage difference² between the left clamp and the electrode under the walking surface (Fig. 2-b). In this way, an electrostatic force is being generated, which pulls the clamp to the surface. Then, the shuffle

² The voltages applied for the clamps and the shuffle plate are at the moment around 50V.

plate voltage is being increased, and due to the same electrostatic force, the shuffle bends and if the voltage applied is greater than a pull-in voltage, the shuffle in fact reaches an unstable region, and clamps to the surface (Fig 2-c). Due to this bending, the distance between the clamps is reduced a little. Subsequently, the right clamp is actuated, and directly thereafter the left clamp is released (Fig. 2-d,e). The last part in the sequence is to decrease the shuffle voltage, such that the shuffle plate bends back to the straight shape and the distance between the clamps equals again the shuffle plate length (Fig. 2-f).

The distance that the μ Walker structure has moved is from hereon called step size. During steady state, the device is suspended by the retraction springs about 500nm above the walking surface. For the shuffle plate, step sizes up to 70nm have been measured, provided that the shuffle plate actuation voltage is above the pull-in voltage. By repeating this sequence with a very high frequency, velocities up to 7.5mm/s can be obtained³.

It has to be noticed, that the pull-in phenomenon of the shuffle plate is of major importance for the proper working of the device as a whole, because it is the subcomponent where the propulsive action is being generated. Therefore, shuffle plate dimensions are of major importance for the force and velocity characteristics of this device.

3. 20-SIM Package

The 20-sim modeling and simulation package is based on object-oriented modeling and simulation concepts. 20-sim has a vast library and is based on an energy consistent description of each component and their interaction. Due to its port-based nature, aggregating system subparts from different domains, for example the electrical, mechanical and thermodynamical domains, is natural and straightforward.

Furthermore, 20-sim also can simulate or export to the Matlab environment the model obtained. 3D animation models can be built in a hierarchical manner. The reader is referred to [11],[12] for more information about this software package.

³ In fact, at the moment the maximum velocity is only constrained by the actuation setup and not by the μ Walker design.

Finally, note that 20-sim not only can model systems with bond graphs [13], but also with iconic diagrams, so that bond graph theory is not required for making models and simulations.

4. Modeling Stick-slip

In many MEMS devices, stick represents a big problem. Measurements are often complex, noisy, time consuming and depend on immeasurable quantities (like local humidity and surface profiles at the contact surface). Humidity and environment temperature influences the measurements considerably, beyond acceptable repeatability constraints. The models obtained from such measurements are often rather empirical than model-based, which increases the complexity when such a model is to be projected on a different device, but with resembling behavior. The consequence is that the problem of stick has not been solved in practice, nor are there any general models which describe this phenomenon satisfactory and in a generalized way, also valid for microsystems, such that predictions can be made on basis of these models. Yet, while stick is and remains a problem in general, the μ Walker moving principle relies for a great deal on it! Not only can the μ Walker enter and leave the stick phase at an arbitrary moment in time, but it can do so in a controlled way, in other words stick can be controlled.

The μ Walker is the first MEMS device to be modeled in 20-SIM. At the moment, several mechanical issues have been addressed, amongst them the stick-slip phenomenon which occurs while the two clamps are shifted over the walking surface. This shall be treated in the following by using a simple mass-spring model and a contact surface featuring the stick-slip phenomenon described by a Stribeck-curve, as presented in Figure 3-a. The code is presented in the Appendix. In this case, we apply a sequence of linearly increasing displacement actuation signals on the right part of the spring, as can be seen in the upper signal plot of Figure 4. The forces acting on the slide surface are the gravitational force F_z on the block and F_{applied} , where the latter is a force applied perpendicular on the block in order to control stick-slip. Now, when the F_{friction} – which is calculated in the slide contact model – is greater than the force exerted by the spring, the block remains on its place, otherwise if the spring force is greater than the friction force,

the block starts moving. In Figure 3-b, the equivalent representation in iconic diagrams is given. Finally, a simulation shows the Stribeck curve in Fig. 3-c.

Figure 3a

Figure 3b

Figure 3c

Figure 4

Provided a mass of 1mg and a spring stiffness of 10kN/m, the simulation is given in Figure 4, where the upper signal is the input, namely the displacement actuation of the right part of the spring. Note that F_{applied} , the perpendicular force applied to the mass, is constant during this simulation. Future work is concerned with fitting this model to the measurements obtained with the μ Walker. These models can easily be extended. For extended information about stick-slip phenomena and other appealing tribology topics, please consult [6],[5].

5. Complete μ Walker model

A complete model of the device has been constructed with iconic diagrams. Figure 5a is a screenshot of the complete model in 20-sim. The reader is referred to [14] for the electro-mechanical model of the shuffle plate, which is not in the scope of this article. Entering the left clamp sub-model gives Figure 5b, where it can be seen how the physical sub-model of the clamp looks like. In the Friction1 block, similar formulas as presented for the mass-spring example in former section describe the governing stick-slip equations.

Figure 5a

Figure 5b

Figure 6

Using the sequential actuation reported in Section 2 gives the simulation result in Figure 6, where each step size is about 47nm. In Figure 7, the displacement of the device as a function of time can be seen. The small circles represent the momentary position, which were obtained off-line with Matlab® from a movie file containing the moving sequence. The step size is about 50nm. Except for (measurement) noise, the model displacement curve in Figure 6 resembles the measurements from Figure 7. The next step will be to have more experiments in order to improve the stick-slip model and thus the correlation between simulation results and measurements.

Figure 7

6. Device optimization and parameter sweeping

Figure 8

Table 1

Finding the optimal sizes and material compounds for MEMS devices can be quite complicated, especially when the number of parameters to be optimized is not very reduced. In the μ Walker design optimisation, the main criteria are the

force delivered, the velocity and the step size. Also power dissipation and step size reproducibility play a role.

An example presents the dimensions involved for the pull-in voltage of the shuffle plate. All sizes shown in Figure 8 can be changed by the parameter optimization toolbox in 20-sim. Not only can device parameters be swept, but also input signals. For the sake of compactness and clarity, only one parameter sweep shall be presented here, where the influence of a repetition of five time shifts between the three the input signals is studied. In Figure 9, it can be seen what the effects are of introducing time shifts for the left and right clamp actuation with respect to the shuffle plate. Because of these shifts, the time periods, when either of the legs and the shuffle plate are clamped to the surface, overlap each other to a certain extent, decreasing the overall step size. The overlap presented in Figure 9 can also be examined by regarding the sequences of Figure 2. First, by applying a delay to the left clamp, the left clamp actuation is retarded so that sequences b) and c) merge, giving rise to a smaller shift than initially. The second signal shift, now back in time, is on the right leg clamp, where the clamping period of the right clamp starts before the shuffle plate actuation is zero. Again, in Figure 2, this means that sequences e) and f) merge to a certain extent. In general, the more overlap between actuation signals, the smaller the step size becomes. The step size now varies from 4.8nm to 65nm. This actuation type can be very useful, when displacements smaller than one step are desirable, i.e. step sizes which are smaller than the maximum step size one can obtain by actuating with a certain set of voltages for the three inputs.

Figure 9

7. Conclusions and remarks

The contact model presented in this paper shows that 20-sim is a proper tool to model the μ Walker contact with the surface and estimate optimal parameters and inputs in the sense of maximizing velocity, force delivery and step size. Due to space constraints, only step size variation has been shown here.

In the future, more attention will be paid to the expansion of the mechanical domain towards the electrical and thermal domains, which will lead to a new, more accurate μ Walker model, including the pull-in phenomenon and more elaborate stiction and friction models. More tribology measurements need to be done for this purpose. The expectation is, that the model will predict resonating frequencies and also accurate positioning behaviour of the device.

It must be noted that any analytical model for the stick-slip phenomenon between contact surfaces can be used, so the model designer is not restricted to the Stribeck model presented here. For instance, one can include state-dependent models, like the Generalized Maxwell Slip friction model [15] shows, featuring several contact points.

The final target of the model to be developed is to use it as a plant in a controller scheme. Because no realtime feedback sensor is available at the moment, using the 20-sim model as the plant in a software environment is the only way to develop a controller. Of course, an imaginary feedback sensor can easily be implemented in software for simulation and control purposes. After such an accurate, predictive model will be available and a real-time sensor will be incorporated in the feedback loop, the optimal controller based on the software model will be validated with respect to the criteria listed earlier.

Regarding measurements, future efforts will result in probabilistic stick-slip results of the μ Walker, so that step sizes dependent on actuation voltages can be accurately simulated and predicted by our 20-sim model.

8. Acknowledgements

We would like to thank E. Sarajlic and G. Krijnen for offering us several μ Walker prototypes for model characterization, as well as for the measurements. μ SPAM is a project (TES 578) funded by the STW Technology Foundation.

9. References

- [1] μ SPAM project website, <http://uspam.el.utwente.nl/>
- [2] Sarajlic E, Berenschot E, Tas N, Fujita H, Krijnen G and Elwenspoek M, High performance bidirectional electrostatic inchworm motor fabricated by trench isolation technology, TRANSDUCERS 05 - Int. Conf. on Solid State Sensors and Actuators - Seoul, Korea, June 2005
- [3] Breguet J-M, Actionneurs "stick and slip" pour micro-manipulateurs, PhD Thesis, École Polytechnique Fédérale de Lausanne, 1998

- [4] Canudas De Wit C, Olsson H, Åström K.J and Lischinsky P., A New Model for Control of Systems with Friction, IEEE Transactions on Automatic Control, Vol.40, Nr.3, Pg.419-425, March 1995.
- [5] Karnopp D, Computer Simulation of Stick-Slip Friction in Mechanical Dynamic Systems. Transactions of the ASME, Journal of Dynamic Systems, Measurement, and Control 85 Vol.107:100-103
- [6] Armstrong-Hélouvry B, Dupont P, Canudas de Wit C (1994) A Survey of Models, Analysis Tools and Compensation Methods for the Control of Machines with Friction. Automatica Vol.30 No7:1083-1138
- [7] Purwanto E and Toyama S, Control Method of a Spherical Ultrasonic Motor, Proceedings of the 2003 IEEE/ASME Int. Conf. on Adv. Intell. Mech. (AIM2003), Pg 1321-1326
- [8] Takemura K, Ohno Y and Maeno T, Design of a Plate Type Multi DOF Ultrasonic Motor and its Driving Characteristics, Proceedings of the 2003 IEEE/ASME Int. Conf. on Adv. Intell. Mech. (AIM2003), Pg.1309-1314
- [9] Ferreira A and Fontaine J-G, Optimized Friction Drive Controller for a Multi-DOF Ultrasonic Nanopositioner, Proceedings of the 2003 IEEE/ASME Int. Conf. on Adv. Intell. Mech. (AIM2003), Pg.1315-1320
- [10] Gnecco E, Nanotribology: Friction Force Microscopy, Encyclopedia of Nanoscience and Nanotechnology, 2004, Vol.7, Pg.879-898
- [11] Controllab Products. (2004) 20-sim, <http://www.20sim.com>
- [12] Weustink PBT, Vries de TJA, Breedveld PC (1998) Object-Oriented Modeling and Simulation of Mechatronic Systems with 20-sim 3.0. Elsevier Science - Mechatronics 98: 873-787
- [13] Amerongen, J van, Breedveld P.C (2003) Modelling of physical systems for the design and control of mechatronic systems (IFAC Professional Brief). Elsevier - Annual Reviews in Control 27:87–117, ISBN S1367-5788
- [14] Ligterink N.E, Patrascu M, Breedveld P.C. and Stramigioli S, An energy-based electroelastic beam model for MEMS applications, Sensors and Actuators A: Physical June 2005, Vol.121, Nr. 2:500-507
- [15] Lampaert V, Al-Bender F, Swevers J (2003) A generalized Maxwell-slip friction model appropriate for control purposes. IEEE Physics and Control 4:1170-1177

10. Appendix

Figure 10

LIST OF FIGURES

Figure 1. One-dimensional version of the μ Walker (Courtesy of E. Sarajlic, University of Twente, The Netherlands).

Figure 2. Possible actuation sequences that lead to a step.

Figure 3a. Mass-spring system with the mass sliding over a flat surface.

Figure 3b. Iconic diagram of the model from Figure 3a.

Figure 3c. Simulation of the stiction/friction curve.

Figure 4. Simulation showing the input velocity, mass position and spring length, respectively.

Figure 5a. 20-sim screenshot of the μ Walker model – top level hierarchy.

Figure 5b. Left clamp model including damping and stiction effects.

Figure 6. From top to bottom: left clamp, right clamp, shuffle actuation and the total displacement, respectively

Figure 7. Measurement showing the displacement due to five consecutive steps of the μ Walker (Courtesy of E. Sarajlic, University of Twente, The Netherlands).

Figure 8. Several dimensions that influence the plate pull-in behavior.

Figure 9. Simulation of one step, while clamp actuation voltages have been shifted; the first three subplots are inputs, while the last one is the output displacement at the center of the device.

Figure 10. The code used for the stick-slip block.

LIST OF TABLES

Table 1. Typical dimensions of the μ Walker under study.

plate width	94 μ m
plate length	180 μ m
plate thickness	1.2 μ m
insulation layer thickness	210nm
distance plate-surface	1.85 μ m

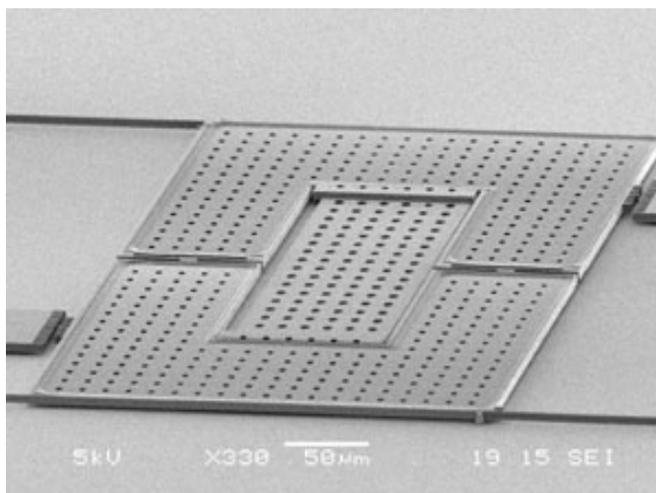


Fig 1

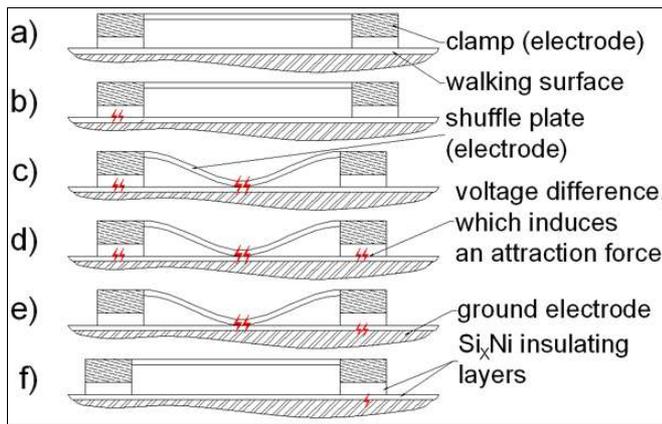
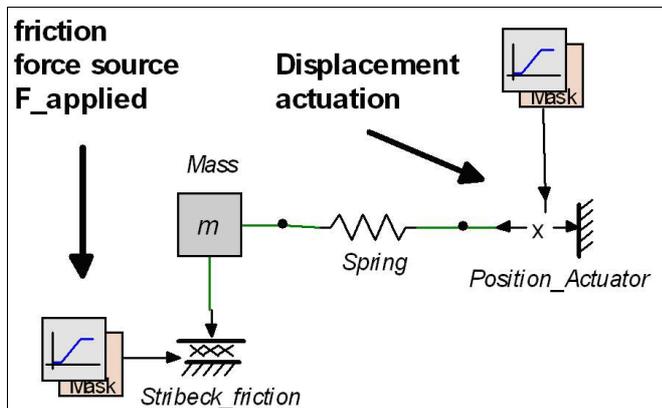
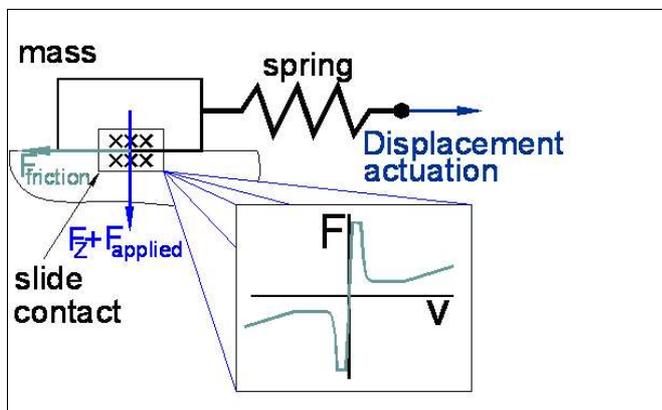


Fig 2



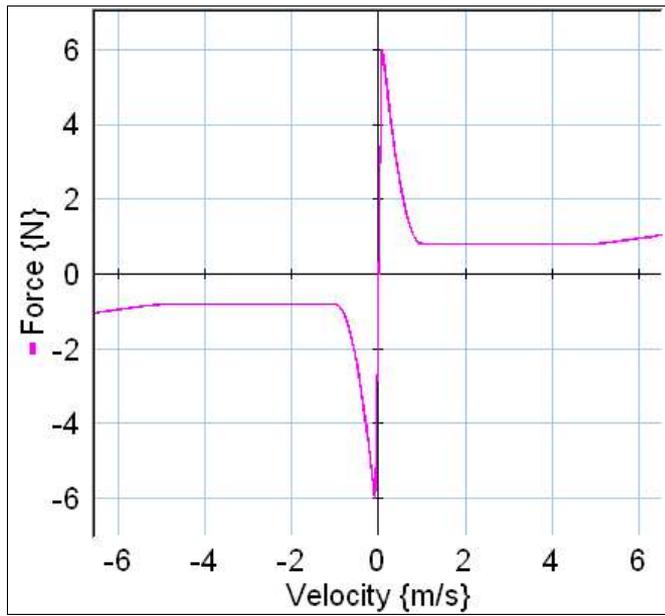


Fig 3a/b/c

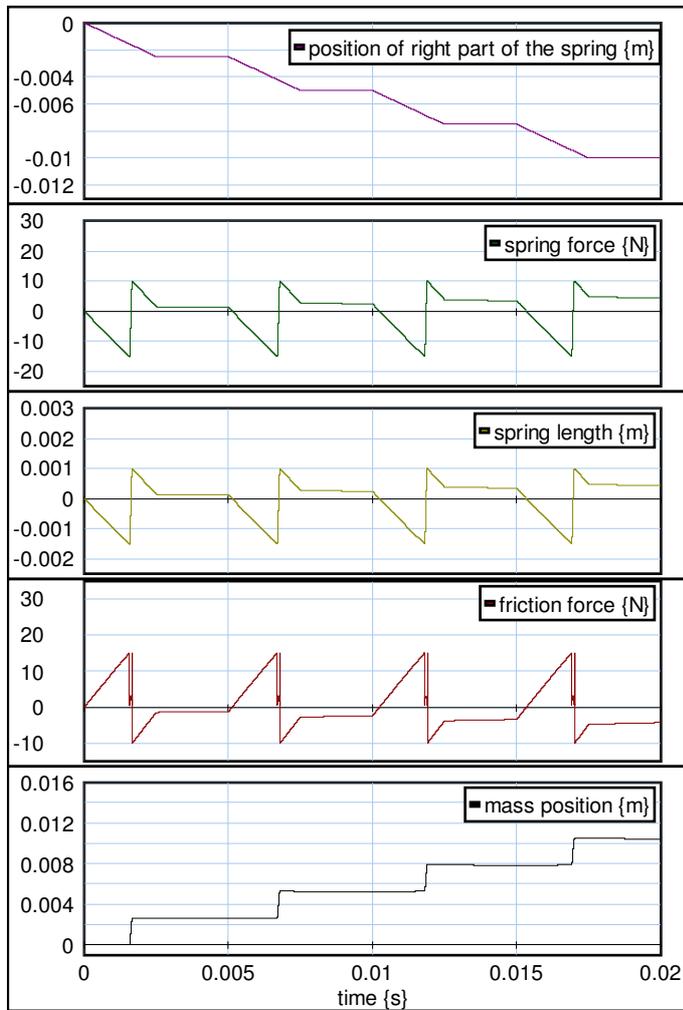


Fig 4

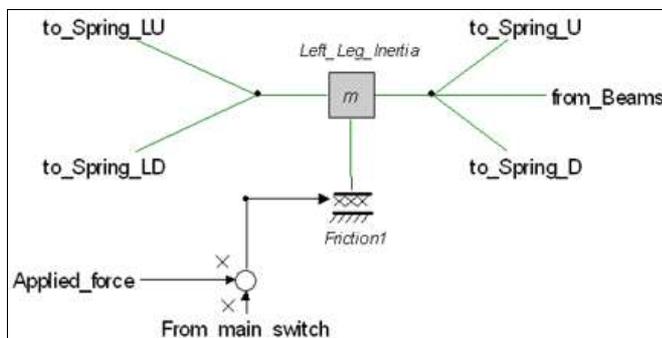
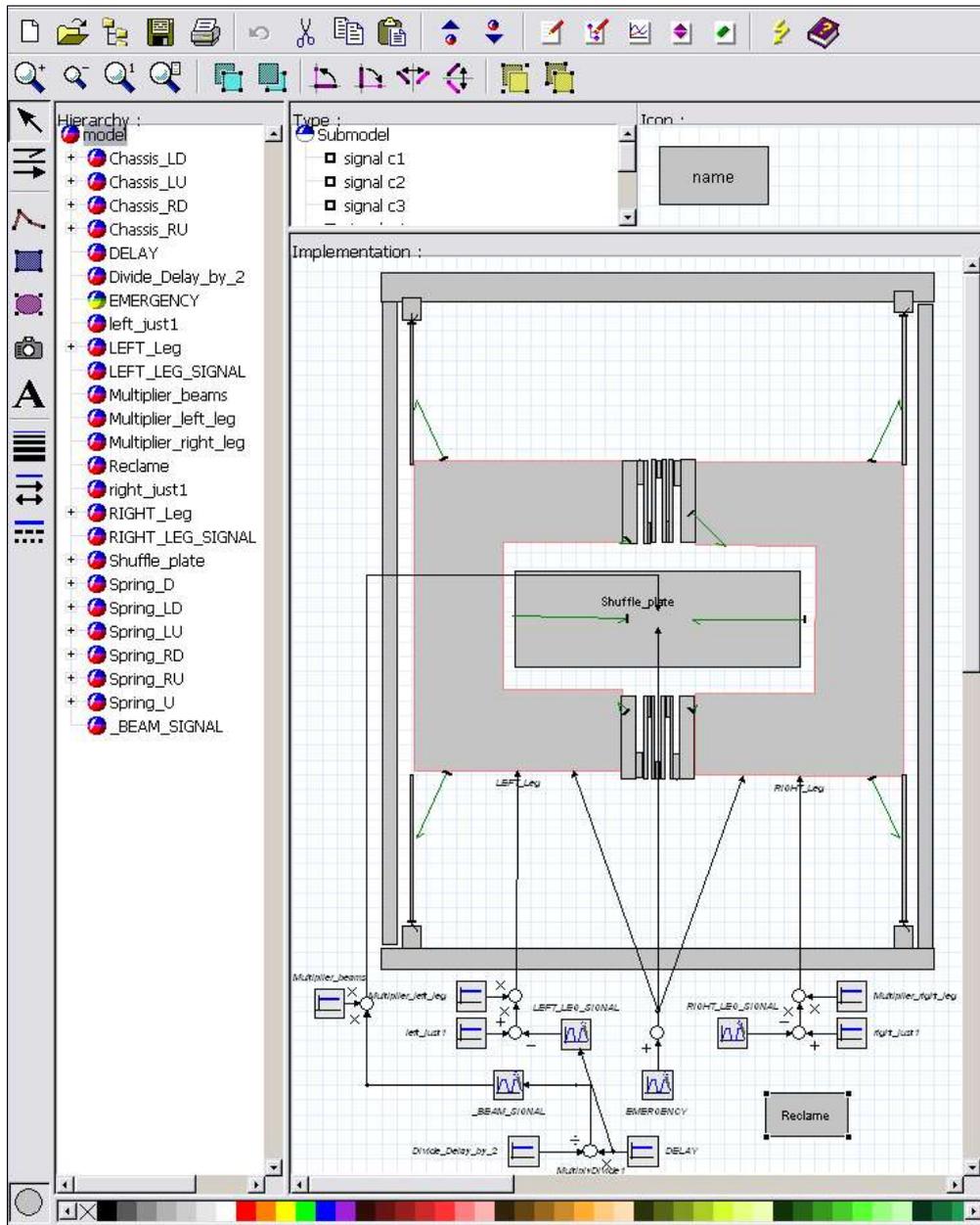


Fig 5a/b

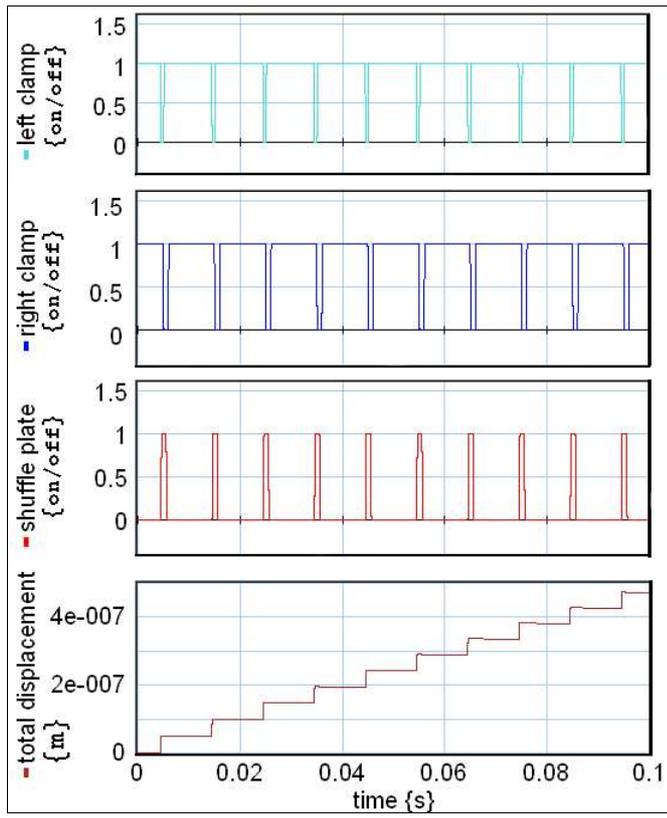


Fig 6

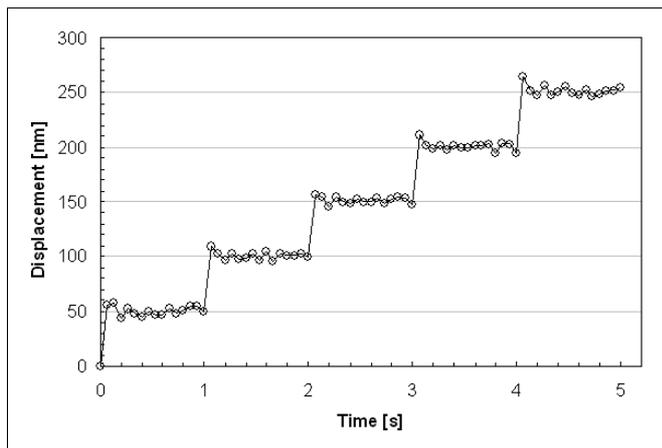


Fig 7

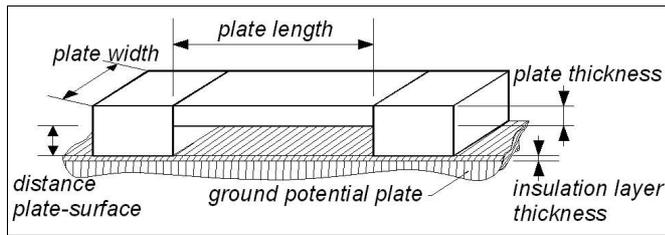


Fig 8

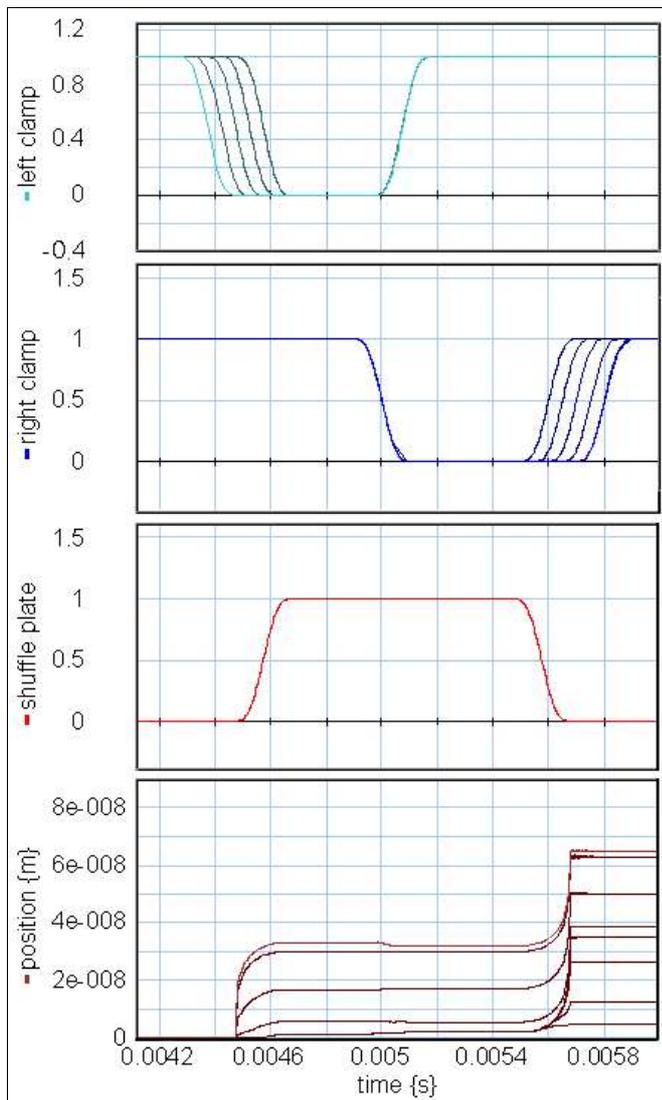


Fig 9

```

parameters
real psi = 0.1; // is ratio: psi = v_breakaway/v_stri_coul
real mu = 0.4;
real epsilon = 0.7; //this is the ratio epsilon = v_springs / v_breakaway

variables
real v_breakaway; //break-away velocity
real x1,x2,y1,y2, r1,r2,r3, X[3,3], y[3,1], abc[3,1];
real F_stri_coul_tot; //total force on the surface, weight + externally applied force
real F_breakaway_tot;

equations
F_stri_coul_tot = mu*(Fn_applied + Fz); //add the weight of the mass
F_breakaway_tot = F_breakaway + Fz;
v_breakaway = psi * v_stri_coul;

//THIS IS THE FIRST REGIME, IT IS LINEAR
if (abs(p.f)<(epsilon * v_breakaway))
    then p.e = (F_breakaway_tot/(epsilon*v_breakaway))*p.f;
end;

//THE SECOND REGIME IS CONSTANT (STICTION)
if (epsilon * v_breakaway<abs(p.f) and abs(p.f)<= (v_breakaway))
    then p.e = sign(p.f) * F_breakaway_tot;
end;

//THE THIRD REGIME DECAYS POLYNOMINALLY (GIVES RISE TO STICK-SLIP)
if (v_breakaway <= abs(p.f) and abs(p.f)<v_stri_coul)
    then
        x1 = v_stri_coul;
        y1 = F_stri_coul_tot;
        x2 = v_breakaway;
        y2 = F_breakaway_tot;
        y = [y1; 0; y2];
        X = [x1^2,x1,1; 2*x1,1,0; x2^2,x2,1];
        abc = inverse(X) * y;
        p.e = sign(p.f) * (abc[1,1]*p.f^2 + abc[3,1]) + abc[2,1]*p.f;
    end;

//THE FOURTH REGIME IS CONSTANT (COULOMB)
if (v_stri_coul<abs(p.f) and abs(p.f)<v_coul_visc)
    then p.e= sign(p.f) * F_stri_coul_tot;
end;

//THE LAST REGIME IS LINEAR WITH SPEED (VISCOUS FRICTION)
if (abs(p.f)>v_coul_visc)
    then p.e = (F_stri_coul_tot/v_coul_visc) * p.f;
end;

```

Fig 10