Modeling of flexible non-linear dynamic links in Nano-Positioning Motion Systems

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Abstract

This paper presents the modelling of the dynamics of a cable schlepp, connected to two moving stages, using a non-linear finite element formulation. The dynamical behaviour of a cable schlepp is non-linear due to the large relative motion of the stages connected to the cable schlepp and the incorporation of end-stops that include contact behaviour. An overview of the finite element formulation is given, including the method with which the initial geometry of the cable schlepp is computed from an un-deformed shape. It is shown how the dynamic parameters of the cable schlepp have been determined; both on the basis of the CAD design and experimentally. The model of the cable schlepp is verified by a set of experiments that have been carried out with both the model and the actual system. The dynamics of the model are in good agreement compared to the dynamics derived with the machine measurements.

Keywords: linearized equations, cable schlepp, identification, test setup, experiment

1 Introduction

In high-speed nano-scale positioning systems, such as the stages used in the wafer scanning industry, high-speed motion is combined with nano-scale tracking precision. In terms of achieving servo performance, the combination of both speed and accuracy puts heavy demands on the control systems and design. The amount of disturbance rejection of the control system is limited due to the fact that the servo bandwidth is restricted by the elastic modes of the wafer or reticle positioning system [1]. Hence it is required to minimize the disturbance forces acting on the stage. A main source of disturbance forces are the so-called dynamic links [2]. These are for instance:

- hoses for transportation of coolant and gas, and
- wires and flexible PCB’s for electrical power and sensor signals.

An overview of the stages in a lithography machine is given in Figure 1a. The flexible links cross between two moving bodies in the stage, for example between the long stroke and the cable shuttle in Figure 1b, where the cable shuttle serves as a cable guide between the base-frame and the long-stroke. With this cross link between stages, movement of one stage is linked to the other, and vibrations of the cable schlepp itself introduce disturbances to the stages. The relative motion between these bodies are small, with movements in the order of \( \approx 1 \) [mm], for the short-stroke and the long-stroke. Large movements (in the order of \( \approx 1 \) [m]) are typical for the long-stroke moves with respect to the base-frame.

This paper will focus on the modelling of the dynamic link between the cable shuttle and the long-stroke, the so-called cable schlepp, as depicted in Figure 1b. With this model, it is tried to achieve a better understanding of the dynamics of the cable schlepp for purposes of developing the mechanical design, and using an accurate model for control purposes, for example in observer systems [3].

The long stroke can freely move in the \( x \) and \( y \) direction, the cable shuttle can only move in the \( y \) direction. The wafer stage is actuated using planar motors, the cable shuttle by a linear motor. The cable schlepp is subject to large non-linear deformations. The motion of the cable schlepp is restricted by means of endstops. To model the cable schlepp endstops the contact dynamics are modelled using a straightforward method, but do also introduce nonlinearities in the cable schlepp model. Special attention will be given to the method in which the model is created and the dynamic properties have been derived.

This paper is organized as follows. In section 2 the non-linear finite element method is introduced [4] that is used to formulate the dynamic equations of the cable schlepp. The method also permits generation of locally linearized models.
used to compute eigenfrequencies and modes. The cable schlepp is assembled in a stress-less flat configuration whereas the cable schlepp in operation has a bend configuration, hence a way to compute an initial configuration of the cable schlepp from a stress-less flat shape is also discussed.

In section 3 the complete model of the cable schlepp will be introduced, including the way in which the non-linear dynamics of the endstops are implemented. The properties of the cable schlepp parts where derived using data from CAD design files. The dynamical properties of the cable schlepp hose and cable assembly where verified using a test setup, in comparison with simulation results. In section 4 these methods used to determine the properties of the cable schlepp will be discussed. The dynamics of the cable schlepp model where verified by means of comparing tests on the lithography machine and simulated experiments. The results of a comparison of the first eigenmode of the cable schlepp are given in section 5, the results of the comparison of the disturbance force exerted on the long stroke in section 6. Finally a conclusion is given in section 7.

2 Finite element formulation

The computer program SPACAR is based on the non-linear finite element theory for multi-degree of freedom mechanisms [4]. The program is capable of analysing the dynamics of planar and spatial mechanisms and manipulators with flexible links and treats the general case of coupled large displacement motion and small elastic deformation. This flexible multi-body approach allows the use of elastic elements (such as beams) within a multibody environment, as well as elements like hinges, wheels etc. The configuration of a multibody system is described by nodal points with coordinates \( x \) and elements with generalized deformations \( e \). The nodal coordinates \( x \) and deformation parameters \( e \) can be written as functions of independent generalized coordinates \( q \) by means of geometric transfer functions \( \mathcal{F}^{(x)} \) and \( \mathcal{F}^{(e)} \),

\[
x = \mathcal{F}^{(x)}(q),
\]

\[
e = \mathcal{F}^{(e)}(q),
\]

where

\[
q = \begin{pmatrix} x^{(m)T} & e^{(m)T} \end{pmatrix}^T.
\]
The independent generalized coordinates \( q \) can be chosen from the components of the nodal coordinate vector, denoted \( x^{(n)} \), and from the vector of generalized deformations, denoted \( e^{(m)} \). Equations (1) can be differentiated to the velocities

\[
\dot{x} = D_q \mathcal{F}^{(x)} \dot{q},
\]
\[
\dot{e} = D_q \mathcal{F}^{(e)} \dot{q},
\]
where \( D_q \mathcal{F}^{(x)} \) and \( D_q \mathcal{F}^{(e)} \) are the first-order geometric transfer functions, with the differentiation operator \( D_q \) represents partial differentiation with respect to the degrees of freedom. Equation (1) can be solved with the Newton-Raphson method [5].

For \( \ddot{\bar{f}} \) defined as in equation (8), this equation can be solved with the Newton-Raphson method [5].

In a certain configuration of the multibody system, the equations of motion (9) can be linearized using small deviations \( \delta q \), \( \delta \dot{q} \) and \( \delta \ddot{q} \) around that configuration, where the prefix \( \delta \) denotes a perturbation. This allows for the analysis of eigenvalues and modeshapes at that specific configuration of the mechanism. The linear approximations of equations (1), (3a) and (4) are given by

\[
\delta x = D_q \mathcal{F}^{(x)} \delta q,
\]
\[
\delta \dot{x} = D_q \mathcal{F}^{(x)} \delta \dot{q} + \left( D_q^2 \mathcal{F}^{(x)} \right) \delta q,
\]
\[
\delta \ddot{x} = D_q \mathcal{F}^{(x)} \delta \ddot{q} + 2 \left( D_q^2 \mathcal{F}^{(x)} \right) \delta \dot{q} + \left( D_q^2 \mathcal{F}^{(x)} \right) \delta q,
\]
and

\[
\delta e = D_q \mathcal{F}^{(e)} \delta q,
\]
\[
\delta \dot{e} = D_q \mathcal{F}^{(e)} \delta \dot{q} + \left( D_q^2 \mathcal{F}^{(e)} \right) \delta q,
\]
where \( D_q^3 \mathcal{F}^{(x)} \) is the third order geometric transfer function.

Expanding the equations of motion (6) with the Taylor series expansions of equations (11a) and (12a), disregarding second and higher order terms, yields the linearized equations of motion

\[
\dot{\bar{f}} = \bar{f}(q, \dot{q}, t),
\]
with the reduced mass matrix

\[
\bar{M} = D_q \mathcal{F}^{(x)^T} M D_q \mathcal{F}^{(x)}
\]
and

\[
\bar{f} = D_q \mathcal{F}^{(x)^T} \left( f - M D_q^2 \mathcal{F}^{(e)} \delta \ddot{q} \right) - D_q \mathcal{F}^{(e)} \sigma.
\]

In order to solve equation (6), the vector of generalized degrees of freedom \( q \) is partitioned as \( q = [q^d, q^r] \), where \( q^r \) are the rheonomic degrees of freedom and \( q^d \) the dynamic degrees of freedom. Substituting this into equation (6) gives

\[
\bar{M}_{dd}(q, t) \ddot{q}^d = \bar{f}(q, \dot{q}, t) - \bar{M}_{dr} \dot{q}^r,
\]
where

\[
\bar{M}_{dd} = D_q q^d \mathcal{F}^{(x)^T} M D_q q^d \mathcal{F}^{(x)},
\]
\[
\bar{M}_{dr} = D_q q^d \mathcal{F}^{(x)^T} M D_q q^r \mathcal{F}^{(x)}.
\]

The stationary solution of a mechanism in a certain configuration is when the vector of dynamic degrees of freedom has a constant value, so \( \dot{q}^d = 0 \) and \( \ddot{q}^d = 0 \). According to equation (9) the stationary solution can be obtained by solving the algebraic equation

\[
\bar{f}(q, \dot{q}, t) = 0,
\]
for \( \dot{q}^r = 0 \), and \( \bar{f} \) defined as in equation (8). This equation can be solved with the Newton-Raphson method [5].
3 Model of the cable schlepp

Figure 2 gives an overview of the complete model for the cable schlepp. The cable schlepp consists of signal and power cables (the cable assembly), and cooling water hoses (the hose assembly). Both are placed side by side in the cable schlepp. Both the cable assembly and the hose assembly are modelled using beam elements. The beam element within the finite element representation can describe both elongation, bending and twisting of a beam between two orientation and position coordinates at the endpoints of the beam. Both assemblies are partially guided by a system of leafsprings and supports. The supports eliminate sideways movements, but are compliant in lengthwise direction. The support bars are modelled as rigid beams, as they can be assumed stiff compared to the flexible elements like hose assembly, cable assembly and leafsprings when only the low frequent eigenmodes of the cable schlepp are of interest.

The ends of the cable schlepp are rigidly attached to the long stroke and the cable shuttle, respectively. The long stroke and cable shuttle are modelled as rigid bodies with a mass in the center of gravity. The attachment of the cable schlepp to the respective stage, an endstop frame is present to prevent movement of the cable schlepp below and above the endstops. The endstop is modelled by placing pinbody elements between the nodes of the leafspring and endstop. The pinbody element within the finite element representation can be used to describe the relative movement and position of two nodes relative to each other. For the linearized model, each of those pinbodies can be either be free moving, or given a certain stiffness and damping according to the constitutive equation:

$$
\sigma_z = \begin{cases} 
0 & z_l > z_e \\
 k(z_l - z_e) + d \dot{z}_l & z_l \leq z_e 
\end{cases}
$$

(15)

where \( \sigma_z \) is the pinbody stress in \( z \), \( z_l \) the \( z \) node coordinate of the pinbody at the leafspring side, \( z_e \) the \( z \) node coordinate of the pinbody at the endstop side, \( k \) is the contact stiffness between leafspring and endstop, and \( d \) a small viscous damping for numerical stability.

The bend geometry of the cable schlepp is unknown in advance. The non-linear equations describing the bend geometry cannot be solved directly in one loadstep. Therefore the geometry is determined in multiple smaller loadsteps, where for every loadstep the stationary solution of the model is calculated.

There are multiple geometric approaches to get from the stress-free configuration, with all beam elements of the cable schlepp undeformed, to the bend geometry of the cable schlepp. One of the methods is to start with an initially flat cable schlepp, as shown in Figure 3a. The nodes at both ends of the flat cable schlepp are translated linearly from the initial to end position and rotated to their orientation using equally spaced loadsteps.

However, the start configuration of the cable schlepp in Figure 3a is a singular configuration, at which the cable schlepp can either move into the configuration of Figure 3a or Figure 3b. When in the configuration of Figure 3b, at some loadstep the Newton-Raphson method for solving equation (14) will not converge. The problem of an initially singular configuration can be partially reduced by using smaller loadsteps. The result of this is that the computing time to calculate...
the bend geometry of the cable schlepp takes a long time, in the order of one hour. The behaviour of the cable schlepp also depends on the mass and stiffness properties, so convergence is still not guaranteed.

For this reason an alternate approach has been adopted using hinges, as shown in Figure 3c, it is possible to create a bend cable schlepp without the problem of a singular geometry. The hinge element describes the relative rotation between two nodes. Using hinges it is possible to initially create the cable schlepp in a triangular configuration, as shown in Figure 3c. Next the hinges are rotated in several loadsteps until the desired bend cable schlepp is obtained. For calculating the bend geometry less steps are needed; for a comparable model like in figure 3a, 10 loadsteps are sufficient. This greatly improves the time needed and is therefore used in the more complex model used later on.

4 Dynamic properties of the cable schlepp parts

The stiffness, mass and inertia parameters of the beam elements used in the cable schlepp model have to match accurately with those of the actual cable schlepp. For most cable schlepp parts it is possible to use data from CAD design files to reconstruct the mass and inertia properties using basic equations. The stiffness properties can be determined when the material Youngs modulus, shear modulus and the geometry are known. For the leafsprings the Youngs modulus was found using material datasheets. For the Youngs modulus of the hose assembly, the stress strain curve was measured from a piece of hose material. The cable assembly is a combination of stranded copper wires in different shapes and sizes, combined to a single flat assembly. While the mass is easily measurable and the inertia calculable, the bending stiffness of such a cable assembly is not trivial to determine.

Experiments were done on the dynamics of the cable assembly to determine the the stiffness properties, and on the hose assembly to verify the calculations. Using a test setup, a sample piece of both a cable assembly and hose assembly were clamped, fixed at one end and freely moving at the other end, see Figure 4. Using a shaker the sample is exited, and using an accelerometer mounted on the sample, the frequency response of the cable assembly due to the excitation is measured. A similar experiment was done using a simulation, where both the cable assembly as the hose assembly where modelled similar as on the test setup. The frequency response of the model is determined by linearizing the model using equation (11a), at which point the input-output relations can be determined [5]. This makes it possible to verify the dynamics of the SPACAR simulation directly with the dynamics measured on the test setup.

The frequency response determined using the test setup and the model are given in Figure 5a for the hose assembly and Figure 5b for the power cable assembly. The frequency responses of both cable and hose assemblies show two clear resonances, one in $x$ and one in $y$ direction as measured by the accelerometer. In Figure 5a there exists a third and fourth mode around 250-300 [Hz], for both the hose and cable assemblies as derived with the model. The measurements also hint to some peaks near this frequency band, but the measured frequency response is too unclear to identify this with certainty due to dynamics of the test setup. For the hose assembly, the eigenfrequency of the first resonance is 6 [Hz] and second resonance is 19 [Hz]. Both match quite well with the frequencies of the modes found with the model. For the cable assembly, the eigenfrequency of the first resonance is 12 [Hz] and second resonance is 29 [Hz], also match well with the model. The associated modeshapes are depicted in Figure 6.
Figure 4: Schematic of the test setup used to determine the frequency response of the hose assembly and cable assembly sample.

Figure 5: Measured and simulated frequency response. - - measured, - - simulated response from $F_x$ to $y$. — measured, — simulated response from $F_x$ to $x$.

Figure 6: Modeshapes of the test cable assembly and hose assembly as determined using the model.
Figure 7: First three modeshapes of the cable schlepp model as determined using the model. Note that the endstops are hidden for clarity.

Figure 8: Measured frequency of the first cable schlepp mode, compared to the first mode of the SPACAR model. Two cable schlepps are measured, two measurements per cable schlepp. ▲, ○, + and • denote the measurements, ◦ are values from simulation.

5 Verification in frequency domain of the cable schlepp model

Figures 7a to 7c show the first three modeshapes of the cable schlepp. The first two modes of the cable schlepp are similar to the modes of the individual samples tested with the test setup and mainly exited by \( x \) moves of the long stroke. The third mode is mainly a rotation of the cable schlepp, and exited by \( y \) moves of the stages.

The frequency of the first mode of the cable schlepp was identified for several positions on two different actual cable schlepps using the frequency response. The plot in figure 8 shows the eigenfrequency of the first mode as function of the long stroke location. On top of this the values found using the model are plotted. For most locations of the long stroke the frequencies identified from the actual cable schlepp and found using the linearization in SPACAR match quite well. The frequency of the first eigenmode from the model is within 10% of the eigenfrequencies measured on the actual cable schlepps.

From 25 [mm] to 125 [mm] however, the frequency of the first mode is overestimated by about 3 to 4 [Hz]. From 0 [mm] onwards, the lower leafspring is starting to roll on top of the lower endstop of the actual cable schlepp. The cause of the over-estimation is that the implementation of the endstop behaviour is lumped at the nodal points and not continuous. At 125 [mm] onwards, the lower leafspring is fully supported by the lower endstop. From this point onwards the contact behaviour between endstop and leafspring does not influence the cable schlepp dynamics.
Figure 9: Acceleration profile for excitation of the cable schlepp.

Figure 10: Plot of the force on the long stroke due to cable schlepp disturbances at 200 [mm] long stroke position, normalized with the maximal feedback force or torque. — experiment, — simulation.
Verification in time domain of the cable schlepp model

To compare the forces that the cable schlepp exerts on the long stroke, an experiment was carried out on the actual system. The cable schlepp was exited by a move of the long stroke in the x-direction with a third order setpoint profile (see Figure 9), while the disturbance forces acting on the long stroke are measured. The model is exited identically, such that a comparison between simulation and experiment can be made. This experiment was carried out on two locations, one at which the first eigenfrequency matched well (200 [mm]) and one at which there was a difference between model and measurement (50 [mm]), see Figure 8.

For the first location, the disturbance forces in both x (Figure 10a) and r_y (Figure 10f) as predicted by the model seem to match quite well with the disturbances measured on the system, both in amplitude, frequency and damping. The machine data show quite a lot of noise (particularly the y data in figure 10b) and disturbances from other sources than the cable schlepp. Nevertheless the damped sinusoidal disturbance of the cable schlepp is easy to identify as it has relatively slow dynamics. At the second location, where the leafspring model does not accurately represent the actual behaviour of the lower leafspring-endstop dynamics, the disturbance forces in x and r_y do not match that well in frequency, and for r_y also some differences in the amplitude are observed, as can be seen in figure 11.

7 Conclusion

The multibody model of the cable schlepp shows promising results when compared to machine measurements. The modeling of the endstops still needs to be improved in order to accurately describe their behaviour. A method has been derived in order to compute the initial configuration of the bend cable schlepp efficiently. Using hinges in the model, the bend geometry of the cable schlepp could be obtained quickly avoiding the occurrence of a singular configuration. The dynamic properties have been derived both from CAD data and from specially designed experiments. In these tests the cable assembly and hose assembly were identified separately and a good agreement was obtained between the modeled
and experimental eigenfrequencies of each part. Next, these parts were combined into a model of the complete cable schlepp. For the first resonance frequency of the model a good match was found with the experimental values in the operating range where the endstops are modelled correctly. Furthermore, the forces and moments acting on one of the stages where predicted quite well in the simulation.

References


