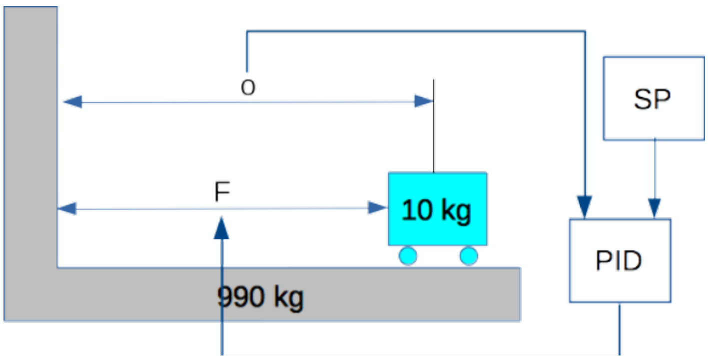
Assignment: Stepper Frame

1 Jerk limited stage control

In early versions of the wafer-stepper an H-drive linear motor system was used to drive the wafer-stage (see appendix 1). On this stage the wafer is supported by a mirror-block. With interferometers, connected to the projection lens, the displacements of the mirror block are measured.

With the driving force acting on the stage and the position sensing devices a position servo system is created. The wafer-stage (10 kg) should make 20 mm steps in about 200 ms. This system should assure a positioning with allowable error signal on the sensors of 0.1 μm. The allowable “settling time”, time between start of the set-point curve and the moment where the accuracy is reached, should be less than 250 ms.

Our first model assumes that the frame is rigidly connected to the ground and that the wafer-stage is a floating mass that is actuated and measured directly relative to the frame.



A step set-point signal is used to instantaneously set the required step of 20 mm.

1. Set up a SimMechanics model according to this Figure. Set the PID-controller to a “bandwidth” of about 80 Hz and observe the error signal as a function of time.

In reality the actuator will have a limited jerk capability due to the combination of the selfinductance and the maximum amplifier voltage. Assume that the actuator can reach a maximum force of 40 N in 2 ms.

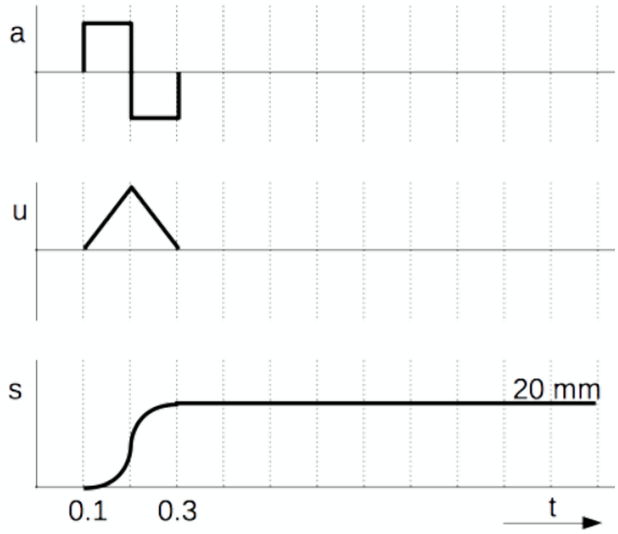
2. Add this actuator limitation to the model by inserting a rate limiter and saturation block immediately before the actuator. Observe the effects on the error by comparing with the previous question.

There are different methods to deal with the actuator saturation that happens when an actuator is asked to deliver more than it is physically capable to. The first method we will implement is aimed at reducing the integrator error in the controller that builds up when the actuator is saturated.

3. Turn on the ‘anti-windup’ feature of the PID controller, and check the error signal again. Because of the very different time-scales that are present in this system, the standard solver of Simulink ‘ode23’ runs very slow. Choose another, ‘stiff’, solver such as ‘ode23s’ (Simulation – Model Configuration Parameters). In addition, set the maximum time step to a smaller value, 1e-5s.

As the error signal is not below 0.1 um after 250 ms an improved setpoint handling method or a better setpoint generator is needed.

Let's replace the step input with a smoother input profile.
We already know that that the system basically consists of a floating mass and cannot accelerate faster than the maximum force of the actuators allows. Therefore an acceleration limited set-point signal is used to smoothly set the required step of 20 mm in less than 0.2 s.



4. Calculate the value for the required acceleration a_{max} to set the desired step.
5. Simulink does not have a profile generator that directly outputs this smoothed step. However it is possible to define the acceleration block signal as calculated in the previous step, and integrate that twice to get the smoothed step signal. Use the summation of 3 step signals to generate the acceleration signal. Check the error signal. Note that the error is still not small enough after 250ms.

A jerk limited setpoint profile where the jerk limit is (just) below the actuator limit will ensure a smooth step without saturating the amplifier. In practice even jerk derivative (sometimes called 'jounce' or 'snap') set point profiles are used. Lambrechts (2003) proposes a simple non-iterative procedure to derive the timing steps for acceleration limited, jerk limited or even jerk derivative limited profiles.

6. Study Lambrechts et al (2003) (on BB), and use the matlab file 'make3' to calculate the timings for a jerk limited set point profile (a_{max} = 2 m/s^2, j_{max} = 2000 m/s^3), and implement this setpoint profile generator in your model and check the error. (Note that because of the limited jerk and a_{max} = 2 m/s^2 this setpoint profile requires a little bit longer than 200ms to step 20mm.) You can use the profile block from the 'motion.mdl' simulink library developed by Lambrechts.

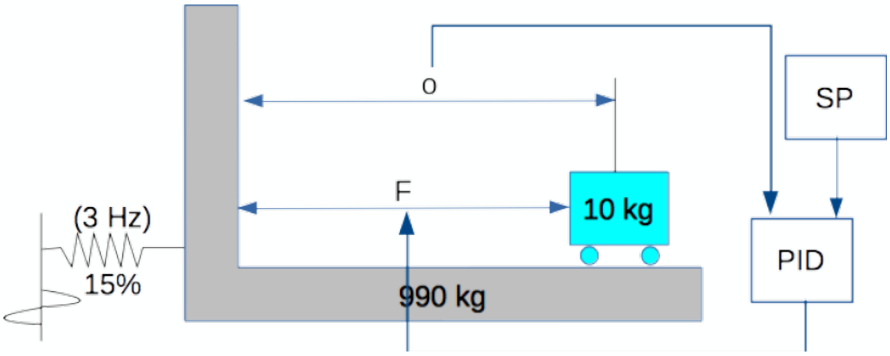
Note that the improvement in this step compared to the previous acceleration limited step is marginal. However, in reality, due to the switching limits of electronic amplifiers in combination with the inductance of electronics, jerk limitation is an important aspect of set-point profile design.

The second method to deal with actuator saturation is in fact to ensure that the actuator does not saturate at all. With feed-forward the *known* behavior of the system in response to *well determined inputs* can be taken into account to determine the required actuation.

7. Implement a rigid body setpoint feed-forward under the assumption that the system is ideal without non-linear limiting factors in the control loop and observe the effect on the position error for 100%, 99% and 90% correct setting of the feed-forward signal.
8. Tune the setting to 100% correct, refresh the simulation, run it again and keep that picture as reference for the next question.

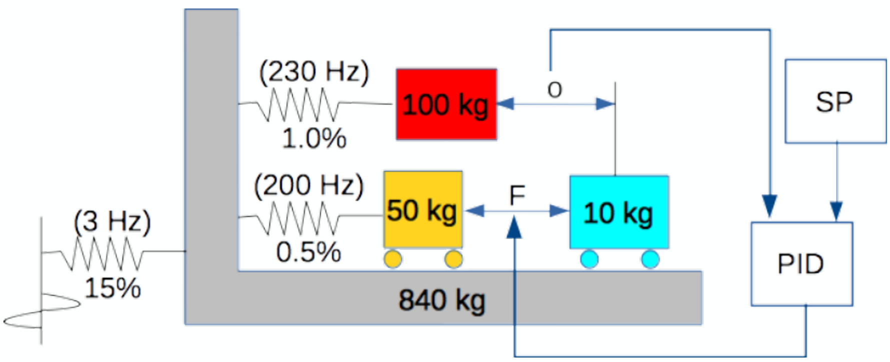
2 Frame vibration induced disturbances

In the real system the machine frame is suspended on air-springs, giving it low frequency support. The typical frequency is about 3 Hz. Due to the reaction forces from the linear motors the frame with the lens and the interferometers will start moving on the soft air-mounts. The motion amplitude might be as large as 0.2 mm and the frequency is 3 Hz.



9. Estimate the required bandwidth based on this given disturbance and the required performance.
10. Make a simulation model for the controlled system. Select proper settings for the PID-controller to achieve the required bandwidth and show that the system will make adequate steps and is capable of dealing with the frame vibration. To tune the PID controller, determine the required proportional gain and use the engineers rule of thumb $\frac{1}{\tau_d} = \frac{1}{3} 2\pi f_{bw}$, $\frac{1}{\tau_i} = \frac{1}{10} 2\pi f_{bw}$ and $N = 10$.
11. Check the stability of this system in the frequency domain.

Considering the frame to be one rigid body is a simplification of the real situation. The linear motor assembly is connected to the frame with a finite stiffness, which, when combined with the moving mass of 50 kg causes a resonance at the natural frequency of 200 Hz, damping 0.5%. Similarly the interferometers unit can be seen as a mass elastically connected to the frame (mass 100 kg, natural frequency about 230 Hz and damping 1%).

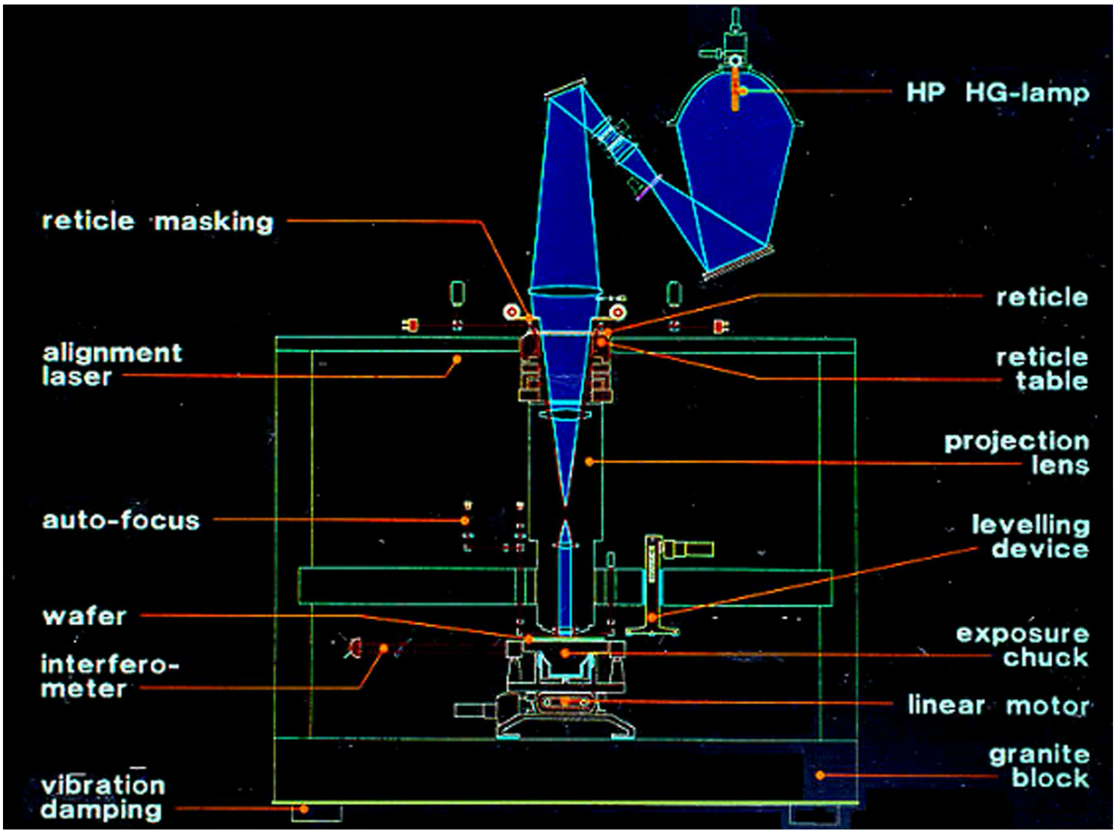


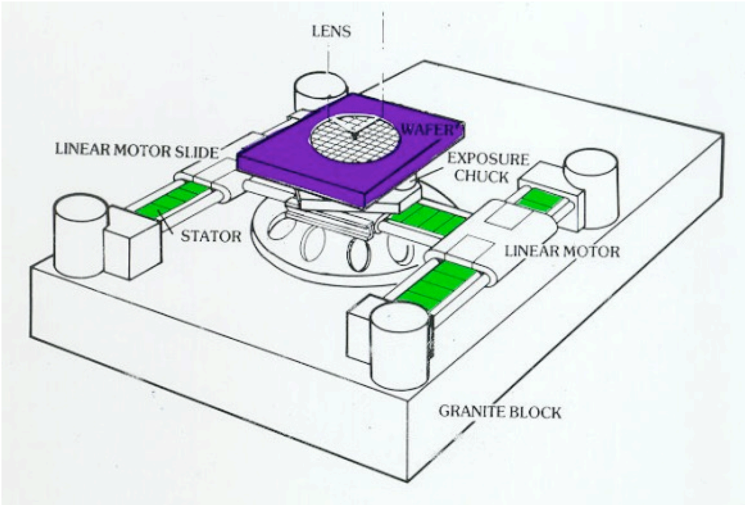
12. Add the two flexible parts of the system to the frame. Re-examine the controller settings and investigate the results.
13. From the previous analysis you will notice that due to internal vibrations of the stage and due to flexibility of the mechanical parts the allowable bandwidth for the system is limited to about 75 Hz. Reduce the controller settings to achieve this value and evaluate the influence on the motion performance.
14. Now, to obtain the required performance, it will be necessary to add additional control or conceptual elements to assure proper performance. You are asked to come up with suggestions and to test the performance using the model.

3 References

Paul Lambrechts, *Trajectory planning and feed-forward design for electromechanical motion systems, version 2*, Report nr. DCT 2003-18, 2003

Appendix 1: An overview of the lay-out of the first generation wafer-steppers




LENS
WAFER
LINEAR MOTOR SLIDE
EXPOSURE
CHUCK
STATOR
LINEAR MOTOR
GRANITE BLOCK