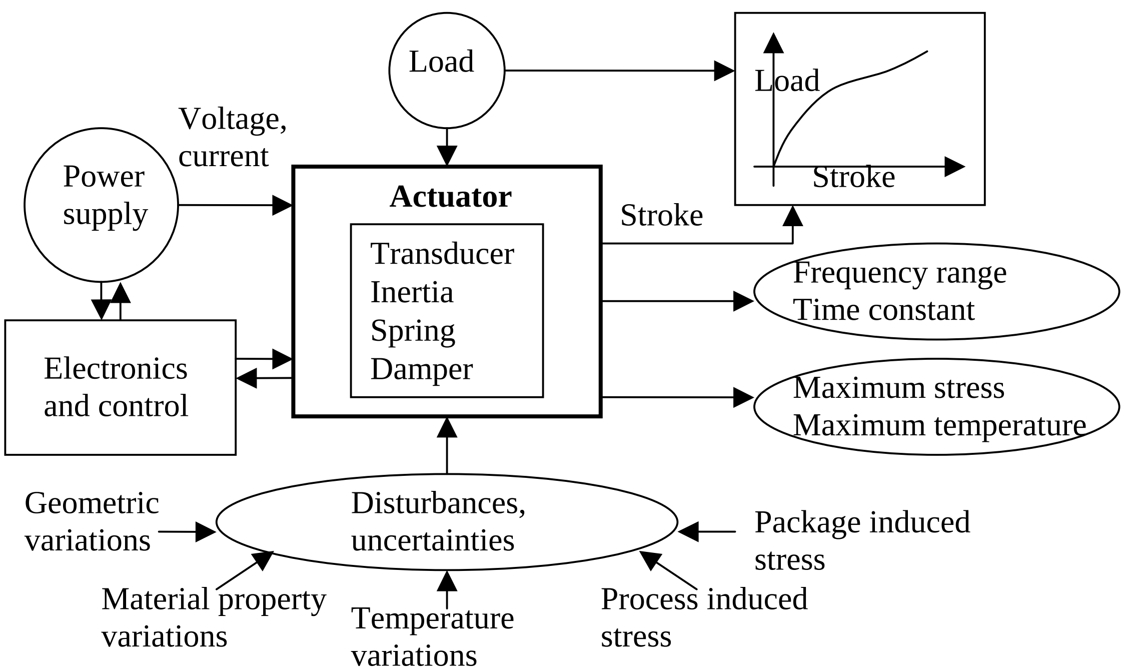
Hierarchical View of the Design Process of Electrostatic Comb-drive Microactuators

System level view of design

When we think about an actuator at the highest level of abstraction, here are some of the questions we ask:

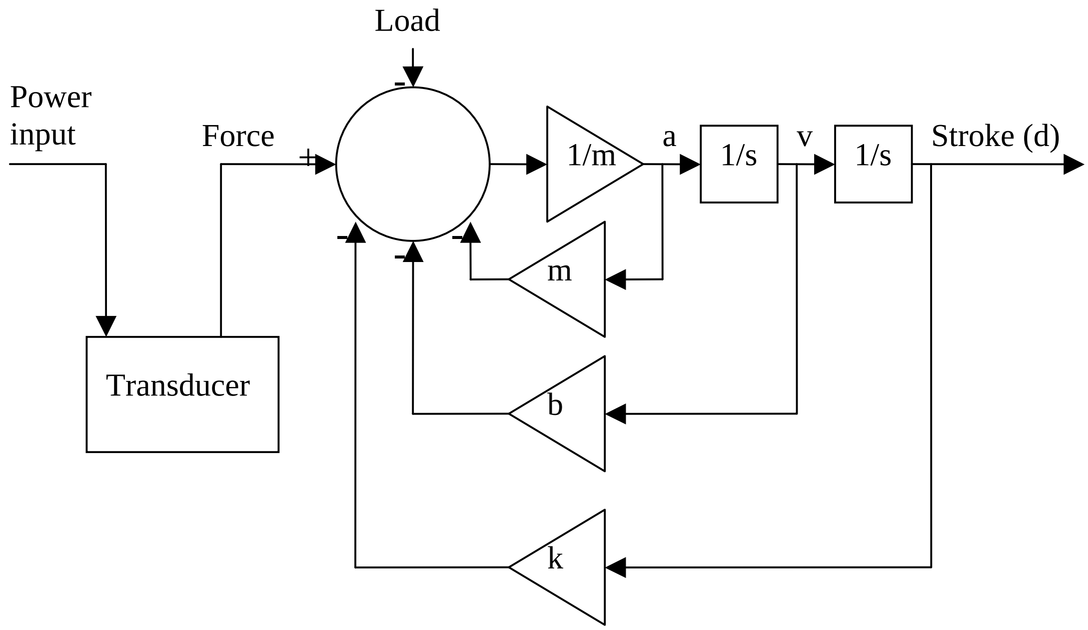
- What are the ranges of strokes (displacements) it can give and loads it can support?
- What is the stiffness of the actuator? That is, how does its force vs. displacement characteristic look like?
- What is its time-constant? That is, how quickly can it respond to an input signal to provide motion or force?
- What is its frequency range? That is, what is the maximum frequency up to which it can follow the input signal?
- What are the effects of temperature on the actuator?
- How sensitive is the actuator's performance to variations in the geometry, material properties, and physical properties?
- How much power does it consume?
- What are the voltage and current (and other power supply related) requirements?
- What are the internal characteristics (e.g., maximum stress, temperature, etc.), that may limit its performance?

All of the above are applicable to the electrostatic comb-drive actuator. Based on the above, a system level block diagram can be drawn as follows.



Device level view of design

If we have a good device-level model for the electrostatic comb-drive microactuator, we can obtain the values of the performance characteristics under different conditions. Or, when we begin the design process, we can specify the levels of disturbances and uncertainties as well as the desired performance attributes. We can also impose some constraints on the power supply. Let us now consider such a device-level model. This model describes the dynamic behavior of the actuator and its parameters depend on the geometry and materials of the actuator as well as the external conditions (which we call disturbances and uncertainties).



The model at the device level is often called a *macromodel* or a reduced order dynamic model of the component or the device. It is supposed to accurately capture the macro effect of the device/component. It should have correct dependence on geometry, material properties, and external (disturbance) conditions. As we can see, in the device-level model of the electrostatic actuator, the parameters for which we need to have expressions that involve geometry, material properties and environmental effects are: m (inertia), b (damping), k (spring constant), and the force generated by the transducing element of the actuator. These are determined by the physics-based equations that govern the respective phenomena.

Physical level view of design

The electrostatic actuator involves three different phenomena: elastic deformations of solids, electrostatics, and fluid damping. The governing equations for the elastic deformation and electrostatic are shown below. The analysis of fluid damping needs some assumptions and we will return to it later on.

Elastic deformations:

Since the deforming parts of the actuator are in the suspension and they can be best modeled using beam theory, we give the governing equations for the deformation of beams.

$$\rho A \frac{\partial w}{\partial t} + EI \frac{\partial^4 w}{\partial x^4} - \sigma_0 A \frac{\partial^2 w}{\partial x^2} = F_{elestrostatic} + F_{fluid}$$

where

ρ = mass density of the material
A = area of cross-section of the beam
w = transverse deflection of the beam
E = Young's modulus of the material
I = area-moment of inertia
and σ_0 = residual stress

Electrostatics:
One can simply use the model of parallel-plate capacitor equations for the electrostatic force. Since the fringing field effects may be significant, we will write here the detailed governing equations form which we can compute the force accurately.

$\nabla^2 \phi = -4\pi\psi$ on the conductors

$\nabla^2 \phi = 0$ in the intervening medium between conductors

$$\mathbf{F}_{elestrostatic} = \frac{\psi^2 \hat{\mathbf{n}}}{2\varepsilon}$$

where
ϕ = electric potential (voltage)
ψ = surface charge density of the conductors
$\hat{\mathbf{n}}$ = normal to the surface of the conductor
ε = dielectric constant in the medium between the conductors

Process level view of design
The electrostatic actuator has such a simple geometry that almost any micromachining process can be used to make it. Thus, not only the surface micromachining process but also bulk micromachining, wafer-bonding, any of high aspect ration processes, etc., can be used. And, they have been used by various researchers. The process we discussed was adapted from the very first surface micromachining process that was used to make this. Later on it is much simplifies to use fewer than four masks.