Introduction to Actuators

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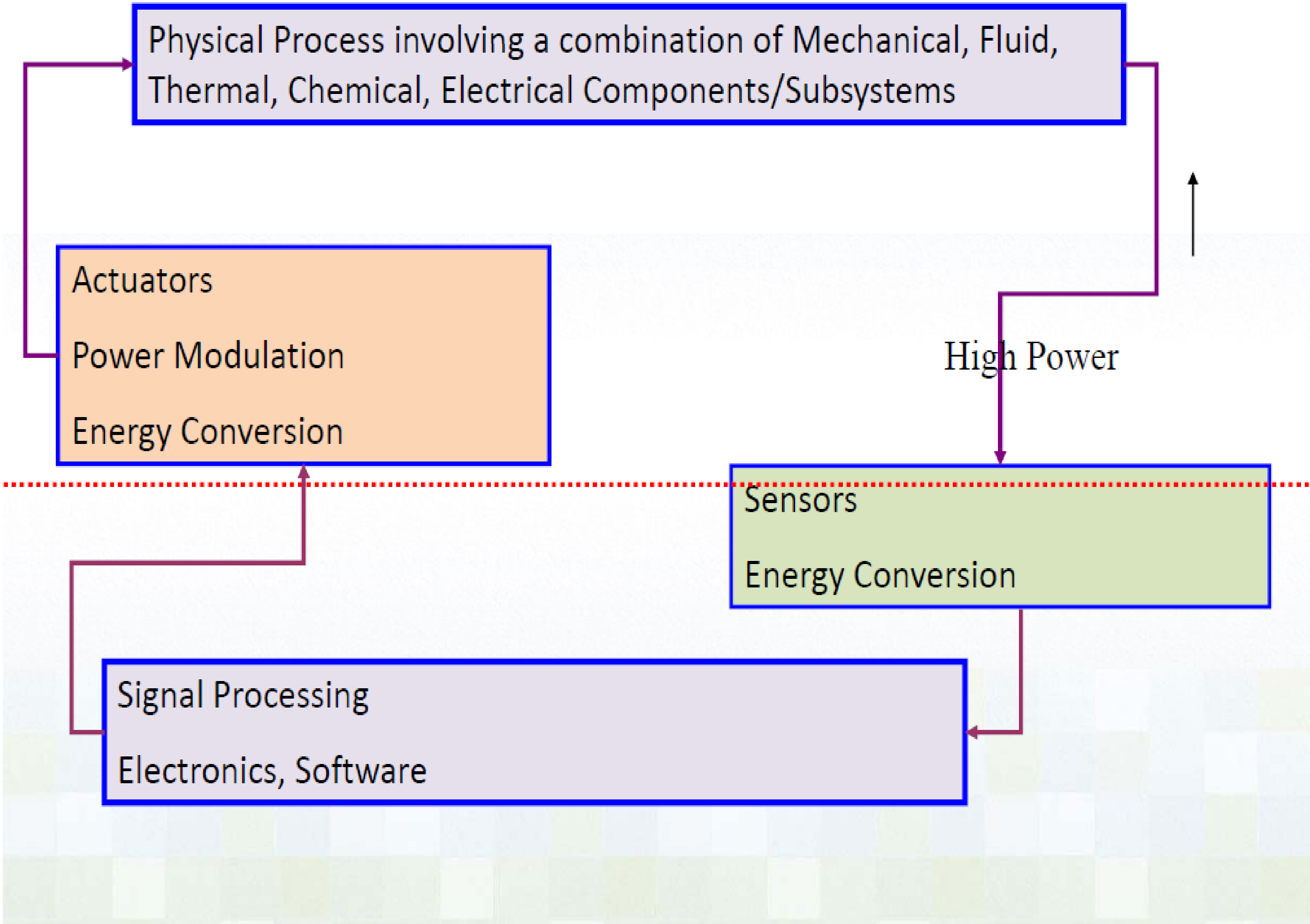
This Lecture Contains

- Why Energy Conversion is needed?
- Energy Conversion in Actuators
- Electrohydraulic (EH) Actuators
- EM based Actuators


Physical Process involving a combination of Mechanical, Fluid, Thermal, Chemical, Electrical Components/Subsystems
Actuators
Power Modulation
Energy Conversion
High Power
Sensors
Energy Conversion
Signal Processing
Electronics, Software

Why energy conversion is needed?

- Fully mechanical systems are possible eg. Store energy in spring (PE) or in Flywheel (KE) and extract as required – toys. However, for such a system:
  - ✓ *closed loop system development is not generally possible*
  - ✓ *energy could not be transferred to a long distance - loss is quite high*
  - ✓ *It will not be green, clean and economic*

Figure 1.2 Manual transmission components: flywheel (1), clutch (2), and gears (3) [12]

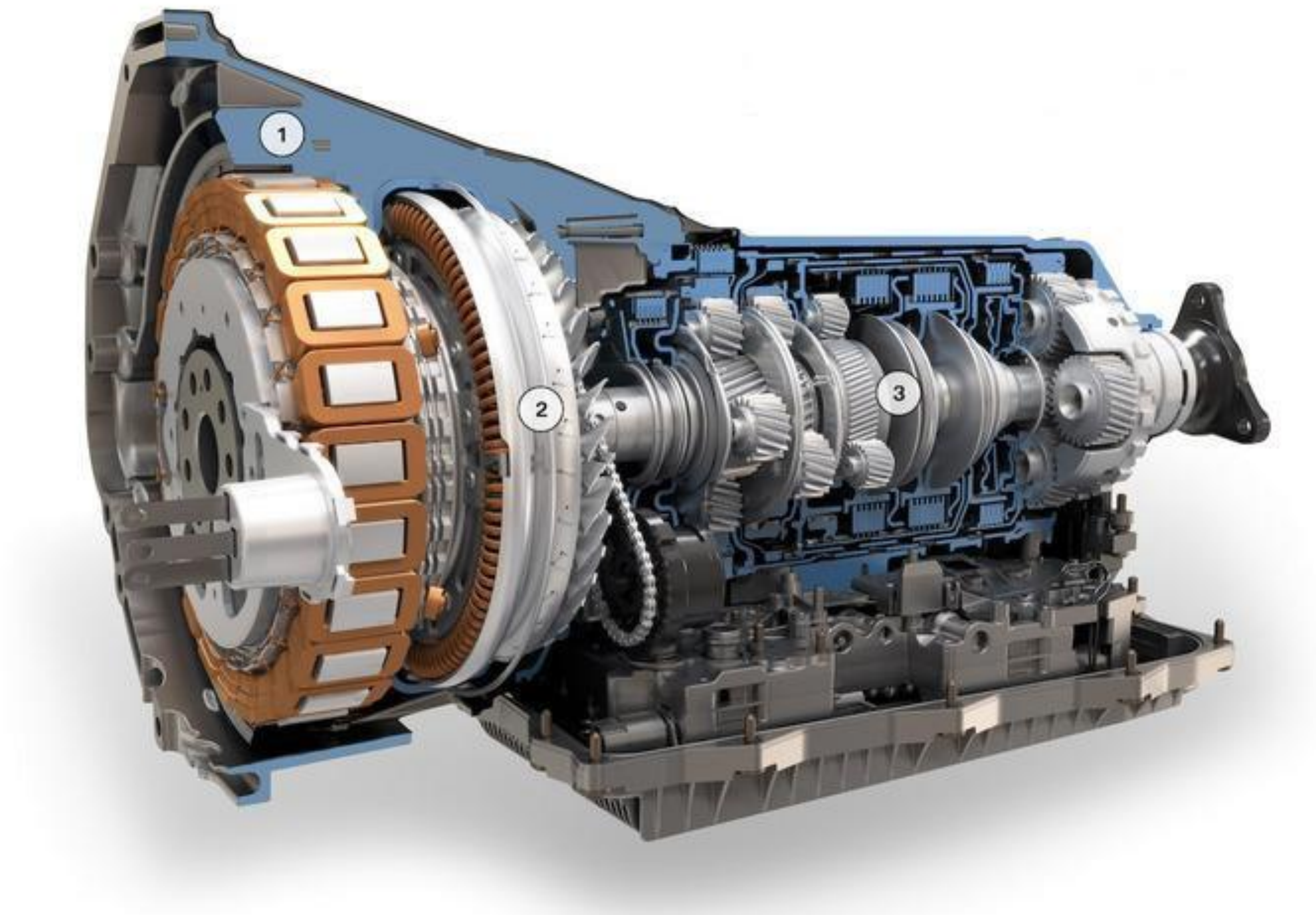
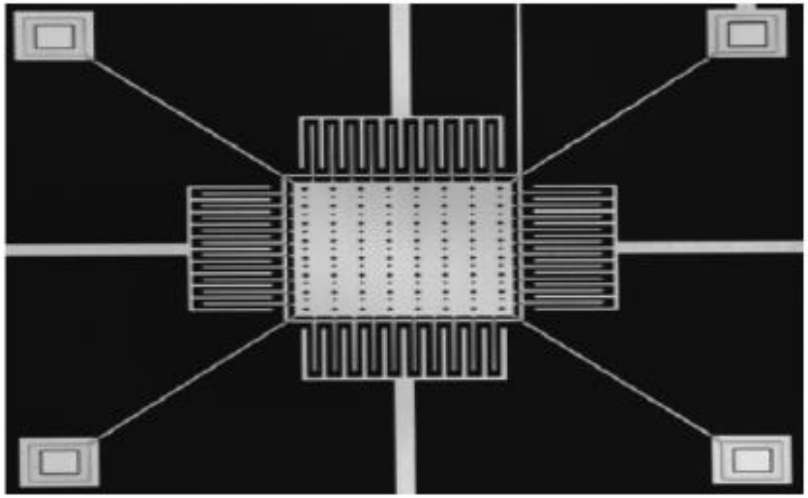


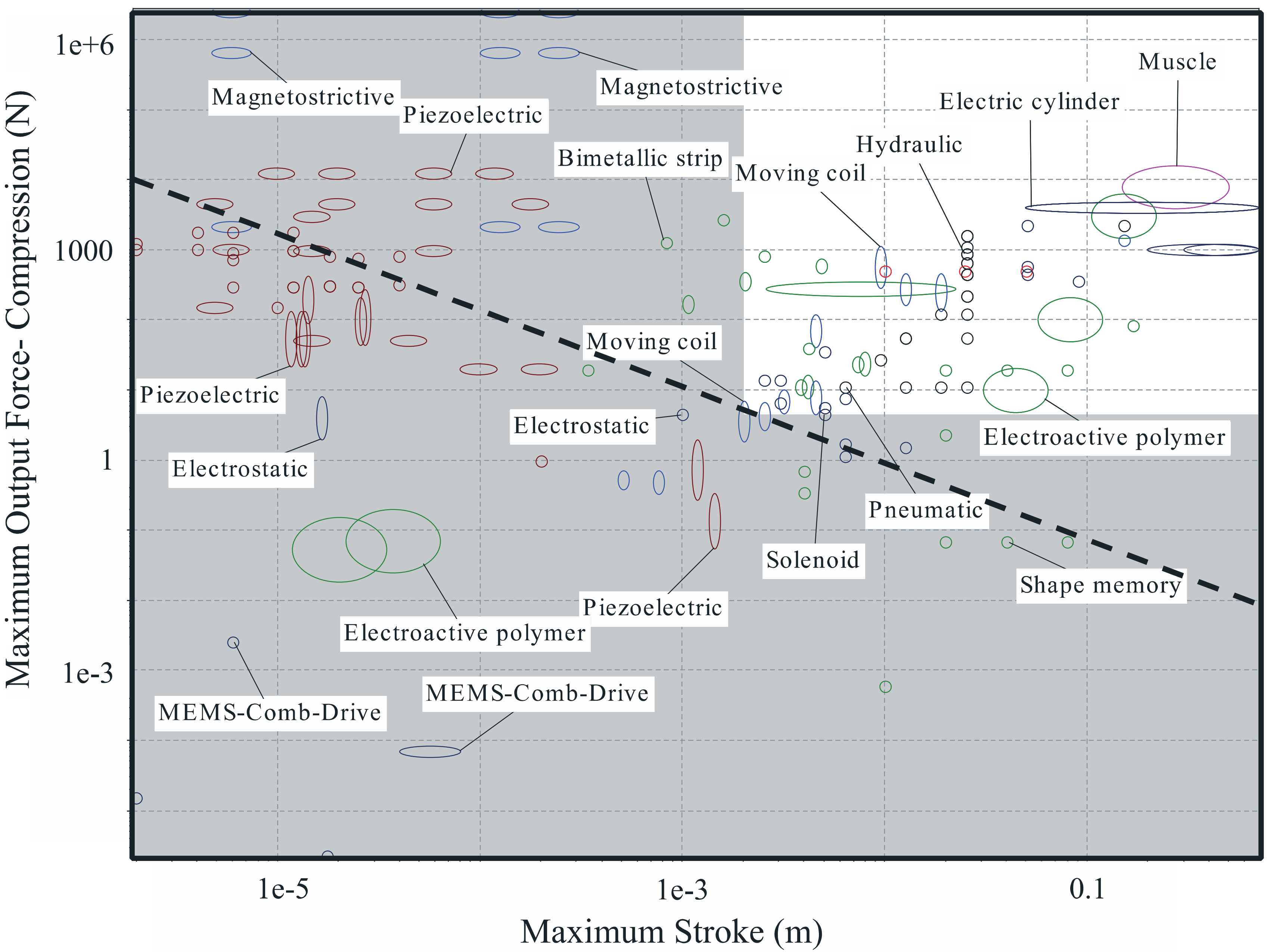
Figure 1.3 Electric motor (1), hydraulic torque converter (2), and 8-speed automatic transmission (3) cutaway in an automatic transmission [13]

Energy Conversion in Actuators

- Electromagnetic : eg. Motors
- Electro pneumatic/Electro-hydraulic
- Electrostatic : MEMS based
- Piezoelectric : eg. PVDF
- Magneto-strictive: Terfenol -D
- Phase-Change related: NITINOL



MEMS based Electrostatic Actuator



Magnetostrictive
Magnetostrictive
Piezoelectric
Muscle
Electric cylinder
Hydraulic
Bimetallic strip
Moving coil
Moving coil
Piezoelectric
Electrostatic
Electrostatic
Electroactive polymer
Pneumatic
Solenoid
Shape memory
Piezoelectric
Electroactive polymer
MEMS-Comb-Drive
MEMS-Comb-Drive
1e+6
1000
1
1e-3
1e-5
1e-3
0.1
Maximum Output Force- Compression (N)
Maximum Stroke (m)

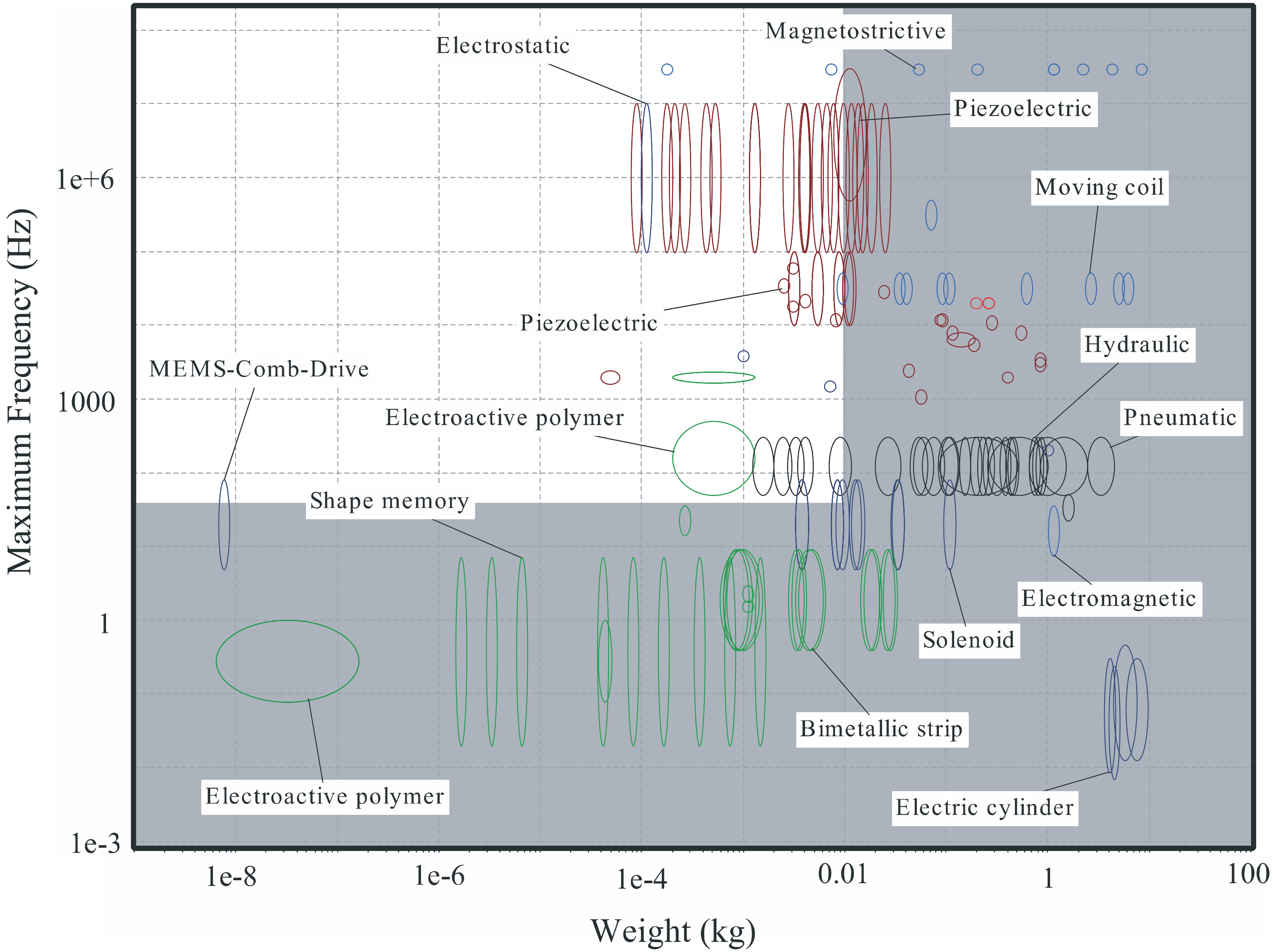
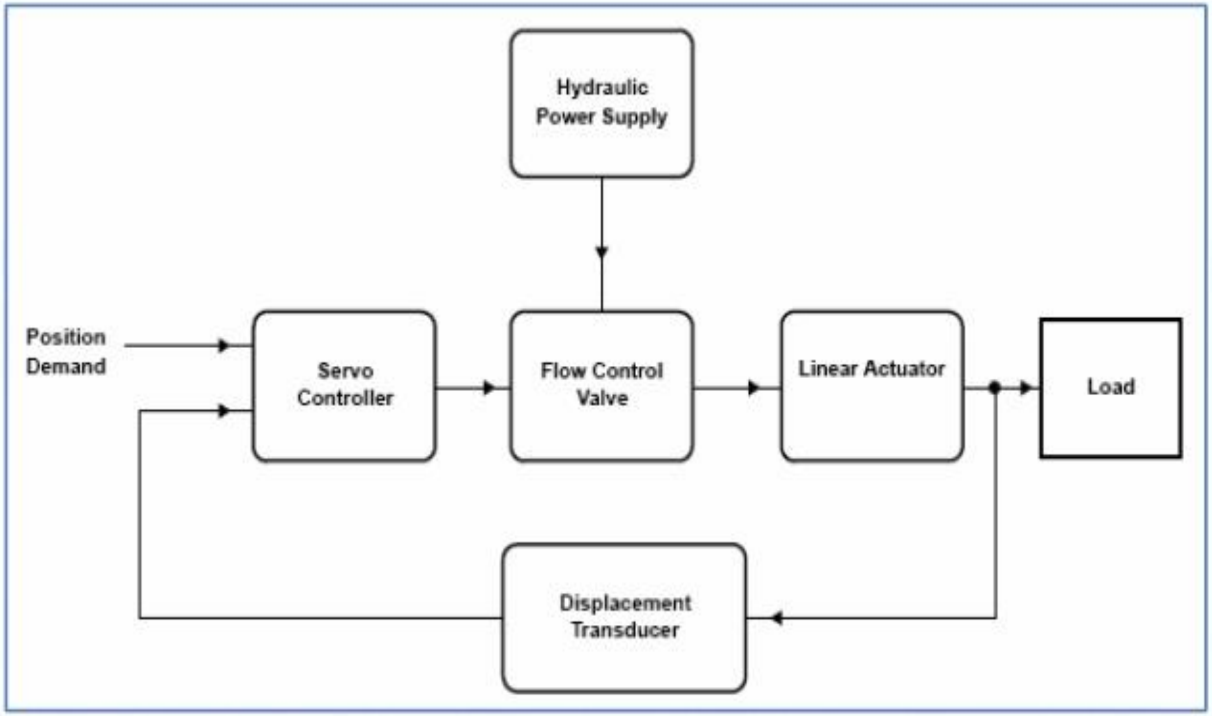
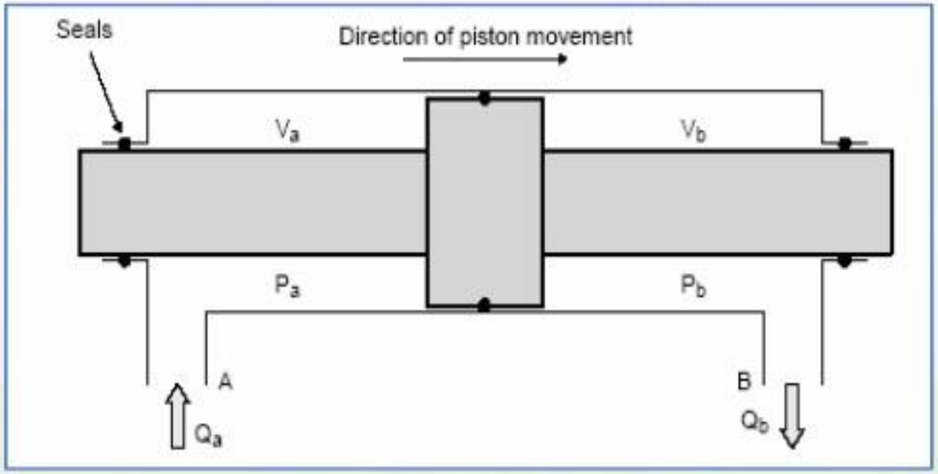


Figure 1.5 A comparison of maximum working frequency versus weight for different actuators [18]

Example of an EH-Actuator





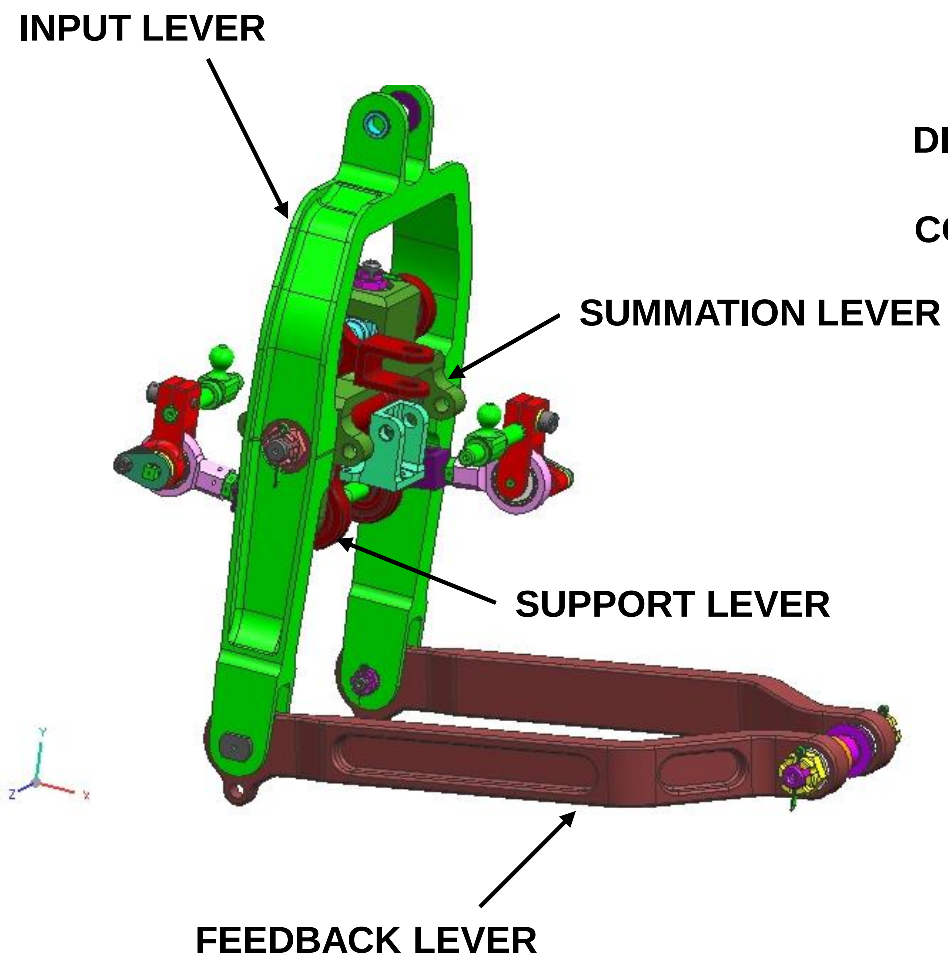
Electro-hydraulic (EH) Actuator

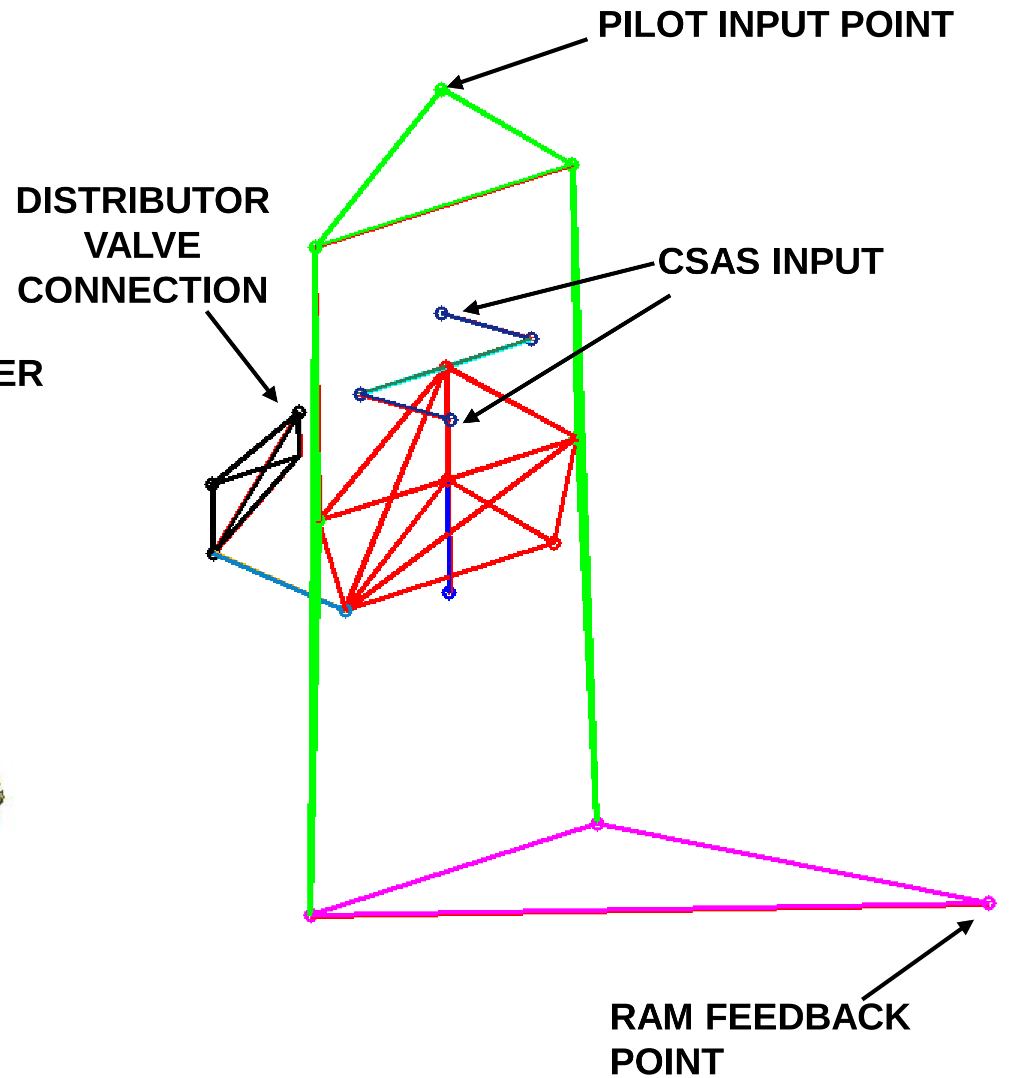
The flow path of such a system could be expressed as:

Motor -> Pump -> Spool Valve/ Poppet Valve -> Accumulator/Pressure Release System -> Loading/Return

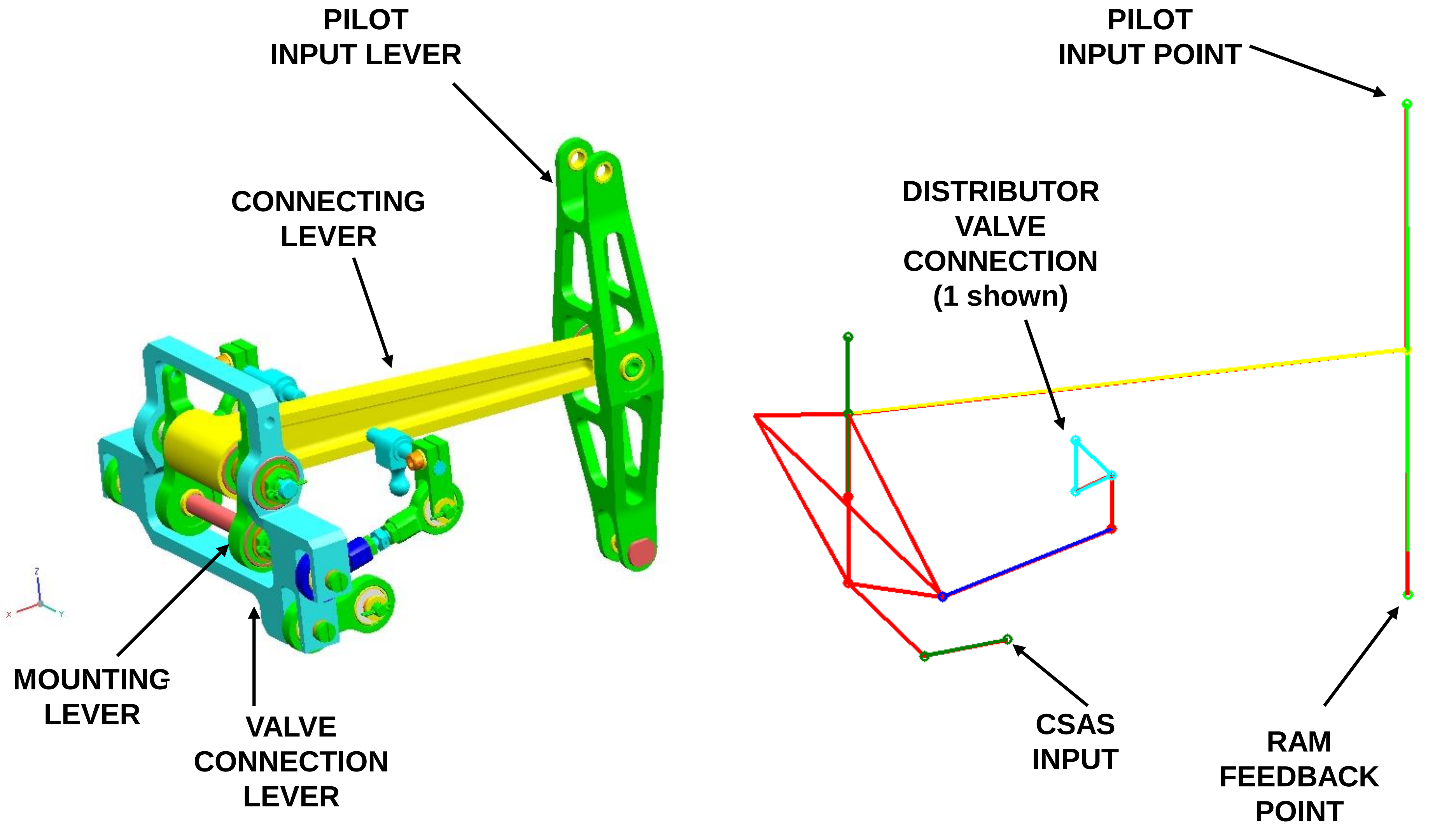
Advanced Light Helicopter: Dhruva

MRA Linkages-Stick Models

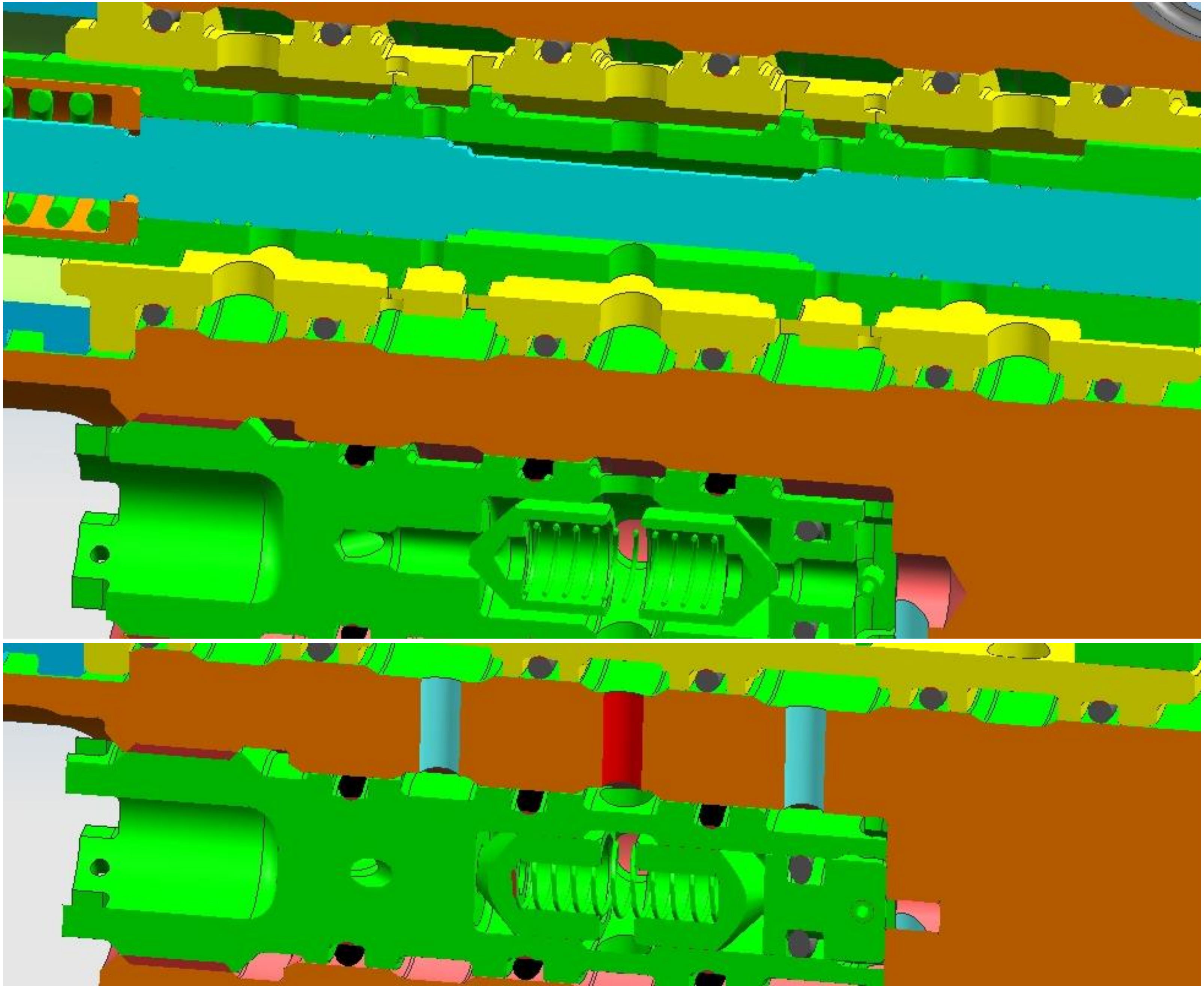




TRA Linkages-Stick Models

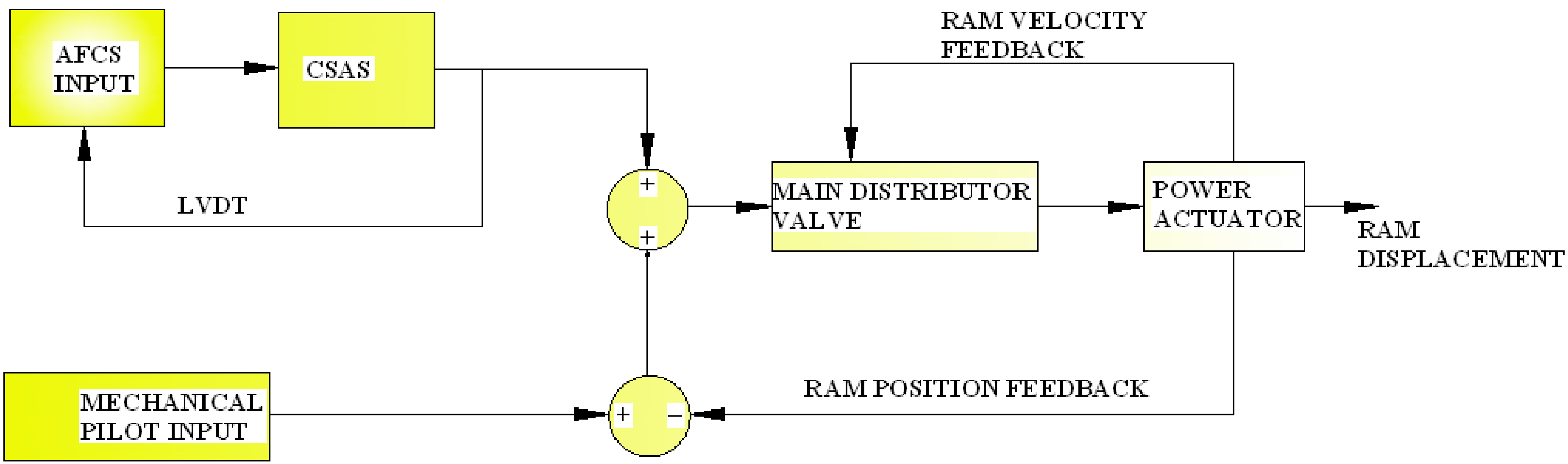


Valve Neutral Position Jam Condition



Functional Diagram- Rotor Actuator

The Functional diagram for the Linear Model of Rotor Actuator is given below and Simulink Block diagrams of Overall Rotor Actuator System has been built on the same lines matching the structure of this block diagram.

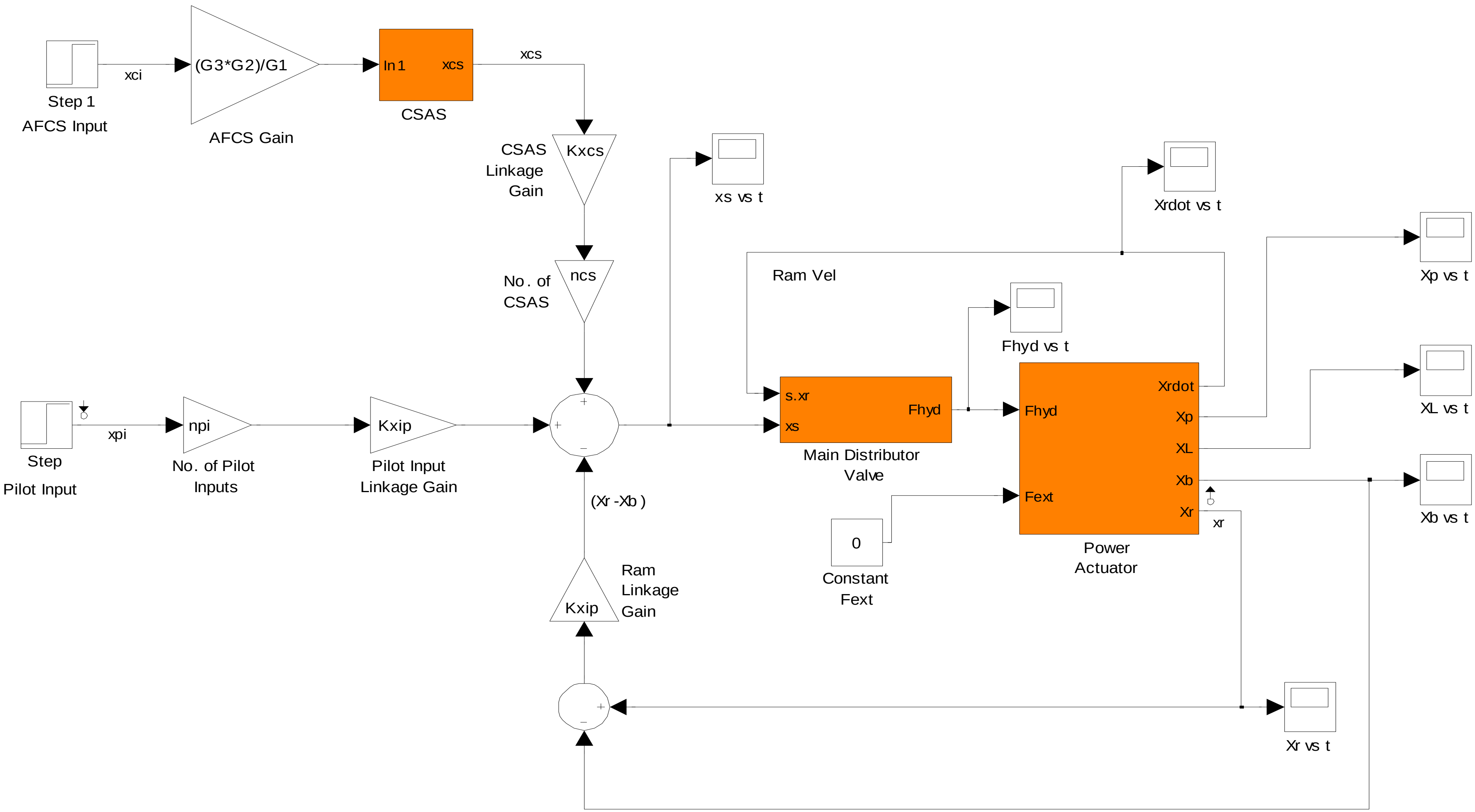


AFCS Automatic Flight Control System

CSAS Control And Stability Augmentation System

Simulink Block diagram: Overall Rotor Actuator

The overall Simulink block diagram is obtained by combining the Simulink Block diagrams of all the modules generated in earlier sections.



Critical Remarks on EH Actuator

- High Force Density
- Can be Mounted Away from the Actuation Point
- Low efficiency due to parasitic losses like viscous and pumping loss, clutch cooling etc.
- Complex due to large number of solenoids
- Leakage of Hydraulic Fluid demands continuous maintenance

Electromagnetic energy conversion

Magnetic field has high energy density than the electric field

Magnetic flux density $B = \mu H$

Lorenz's Law

Force realized by a current carrying conductor of length L

$$|F| = Bli$$

Faraday's Law:

Motion of a conductor in a magnetic field will produce EMF

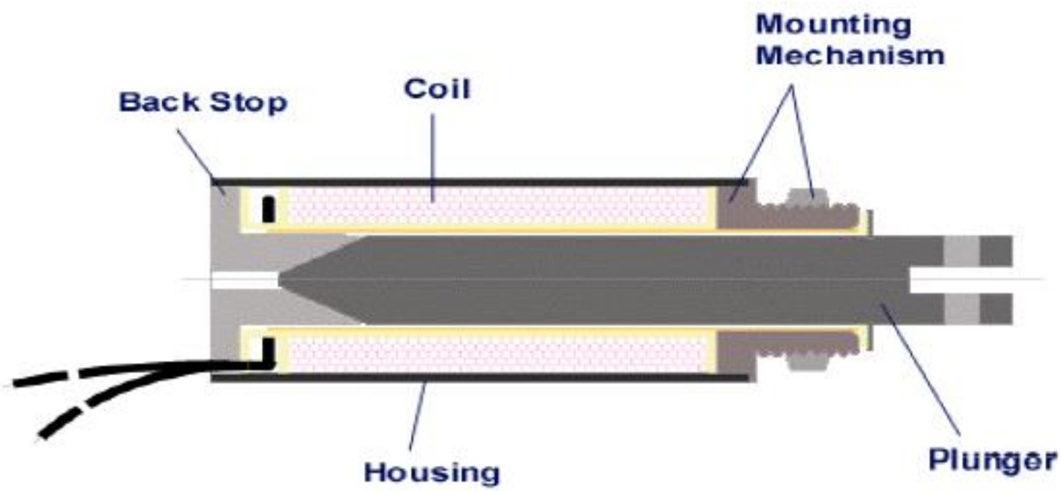
$$E = -d\varphi/dt = BLv$$

Types of EM based Actuator

- Solenoids(EM) /EH/EP actuator
- DC Motors (with bruss/ brussless)
- AC Motors (synchronus/)
- Stepper Motors

A solenoid is a long wire, wound with a helical pattern, usually surrounded by a steel frame, having a steel core inside the winding.

When carrying a current "i ", the solenoid becomes an electro -mechanical device, in which electrical energy is converted into mechanical work.



Efficiency of a solenoid depends on: Geometry, Electrical Configuration and Magnetic permeability of the three subsystems - core, plunger and housing.

The plunger is free to travel in the center of the winding in a linear mode. When the coil is driven by an electric current "i ", a magnetic force is created between plunger and the end core, causing the plunger to move. The higher the permeability of steel used, the better will be the performance.

It is essential for a solenoid to lose its magnetic force as fast as possible when the input electrical power is removed. This is to allow the plunger to resume its original position. Any remaining magnetic field is residual magnetism.

To obtain the optimum performance, reliability and life of a solenoid, selection considerations should include the following factors:

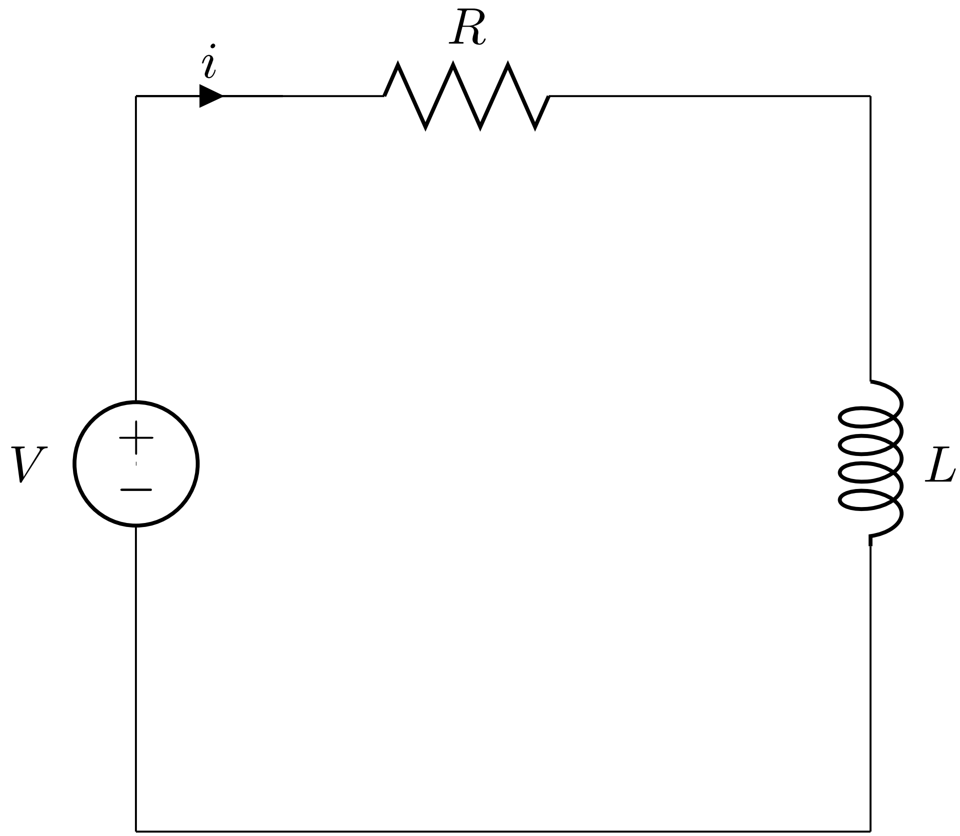
1. **Force or Torque**

Pull, push or rotary load, developed by plunger when the coil is activated by an external voltage.

2. **Stroke**

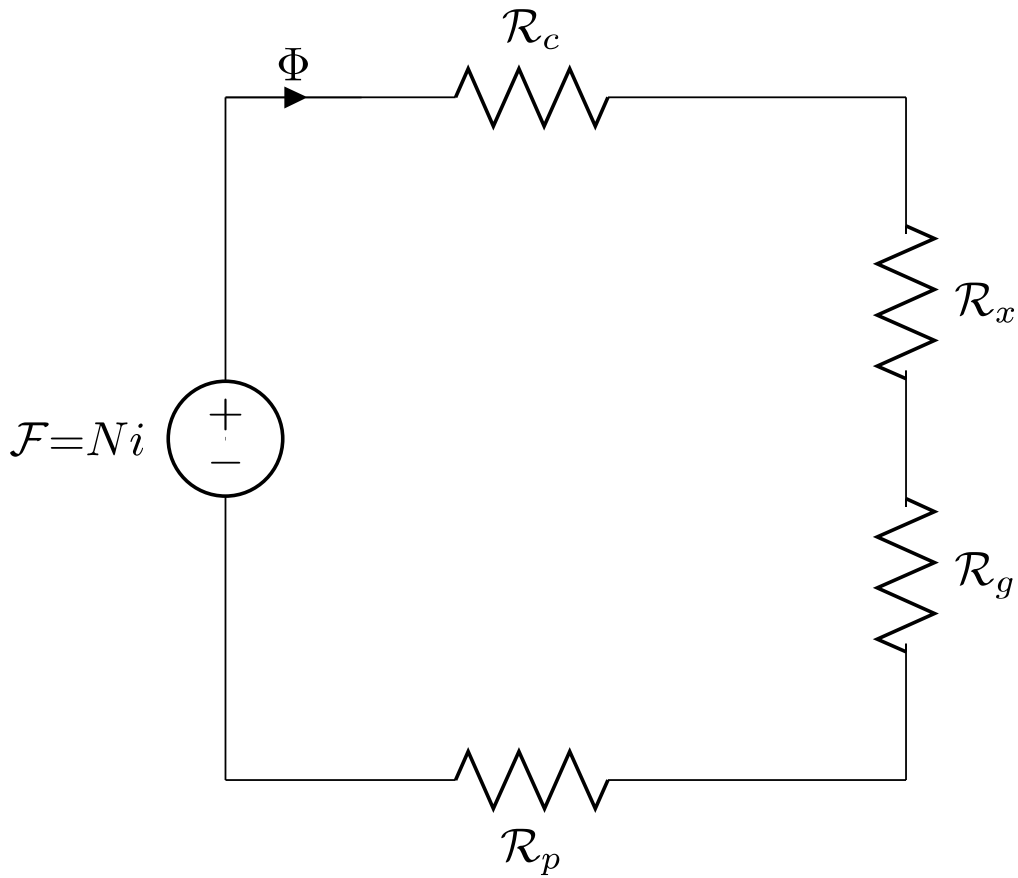
The distance a plunger must travel before it is stopped.

The force versus stroke relationship must be known for any particular solenoid to be used. This relationship is usually shown as a characteristic curve.



$$V = Ri + L\frac{di}{dt} + i\frac{dL}{dt}$$

$$V = Ri + L\frac{di}{dt} + i\frac{\partial L}{\partial x}\frac{\partial x}{\partial t}$$



$$F_e(i,x) = -\frac{1}{2}i^2\frac{N^2\mu_0 A_f A_g^2}{(A_f g + A_g x)^2}$$

$$\mathcal{F} = \mathcal{R}\Phi \qquad L(x) = \frac{N\Phi}{i} \qquad L(x) = \frac{N^2}{\mathcal{R}}$$

$$F_e = \frac{\partial W_c(i,x)}{\partial x} \qquad W_c(i,x) = \frac{1}{2}L(x)i^2$$

$\mathcal{R}$ can be regarded as the summation of reluctances of different components

$$\mathcal{R} = \mathcal{R}_c + \mathcal{R}_x + \mathcal{R}_g + \mathcal{R}_p \tag{2.9}$$

where $\mathcal{R}_c$ is the core reluctance, $\mathcal{R}_x$ is the reluctance of the main air gap, $\mathcal{R}_g$ is the reluctance of the secondary air gap and $\mathcal{R}_p$ is the reluctance of the plunger. The reluctances can be calculated as follows

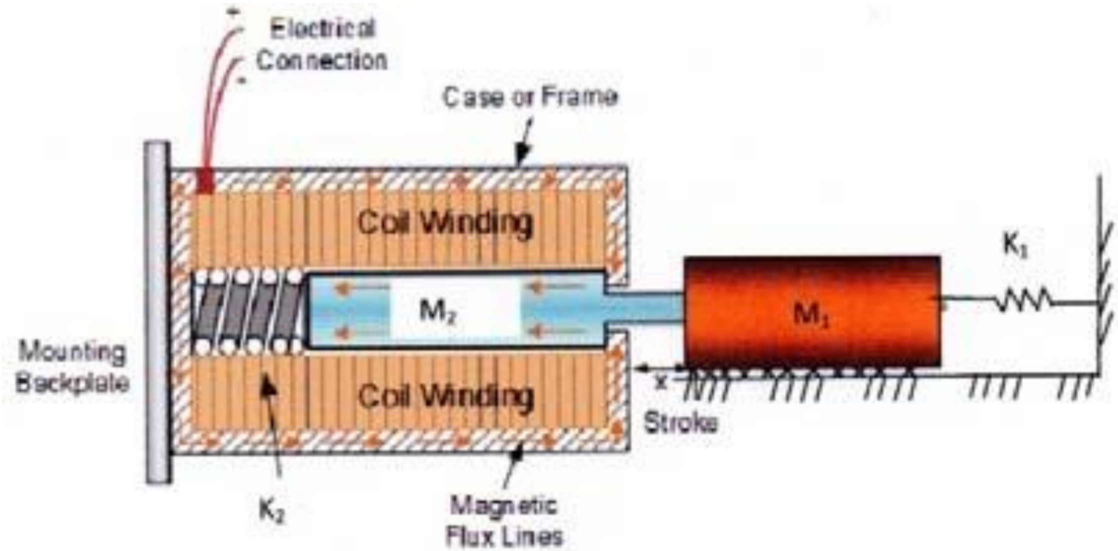
$$\mathcal{R}_c = \frac{l_c}{\mu_f \mu_0 A_f} \tag{2.10}$$

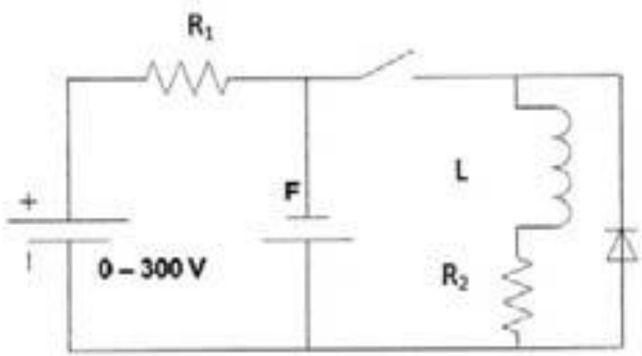
$$\mathcal{R}_x = \frac{x}{\mu_0 A_f} \tag{2.11}$$

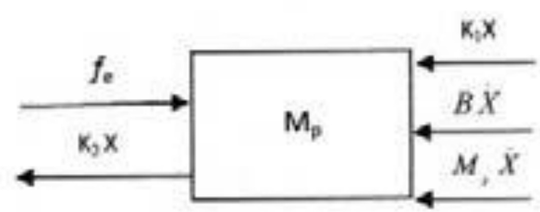
$$\mathcal{R}_g = \frac{g}{\mu_0 A_g} \tag{2.12}$$

$$\mathcal{R}_p = \frac{l_p - x}{\mu_f \mu_0 A_f} \tag{2.13}$$

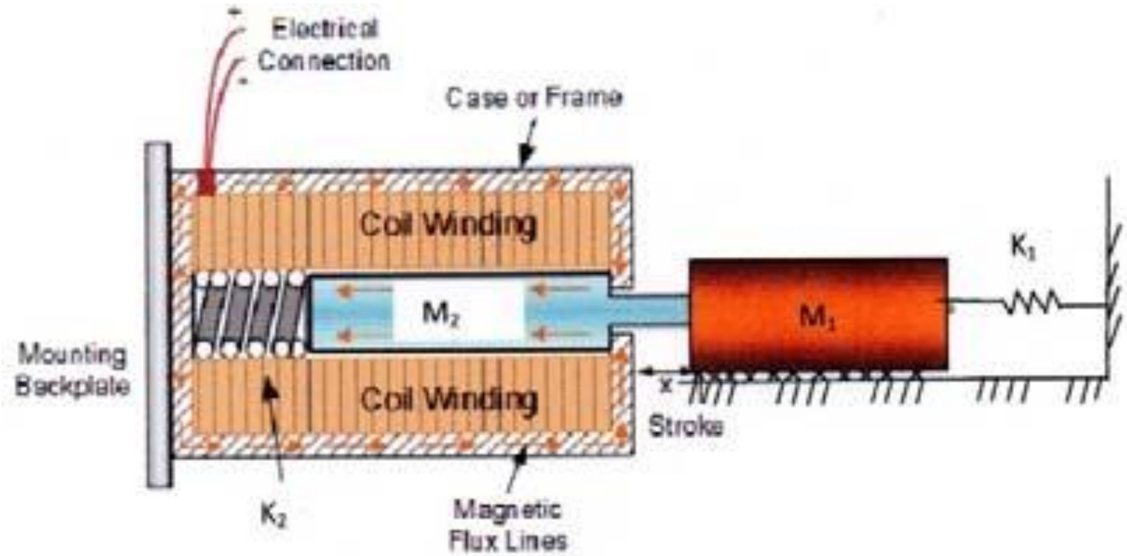
Solenoid Valve

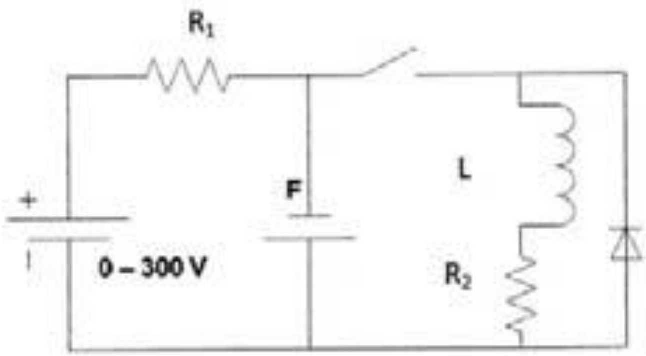


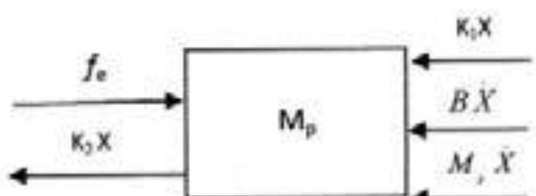




A Solenoid Valve Model







Proof Mass Actuator

Active DVA

Now, we will consider another active DVA commonly known as **proof mass actuator**. The basic system is described in Fig. 19.2.

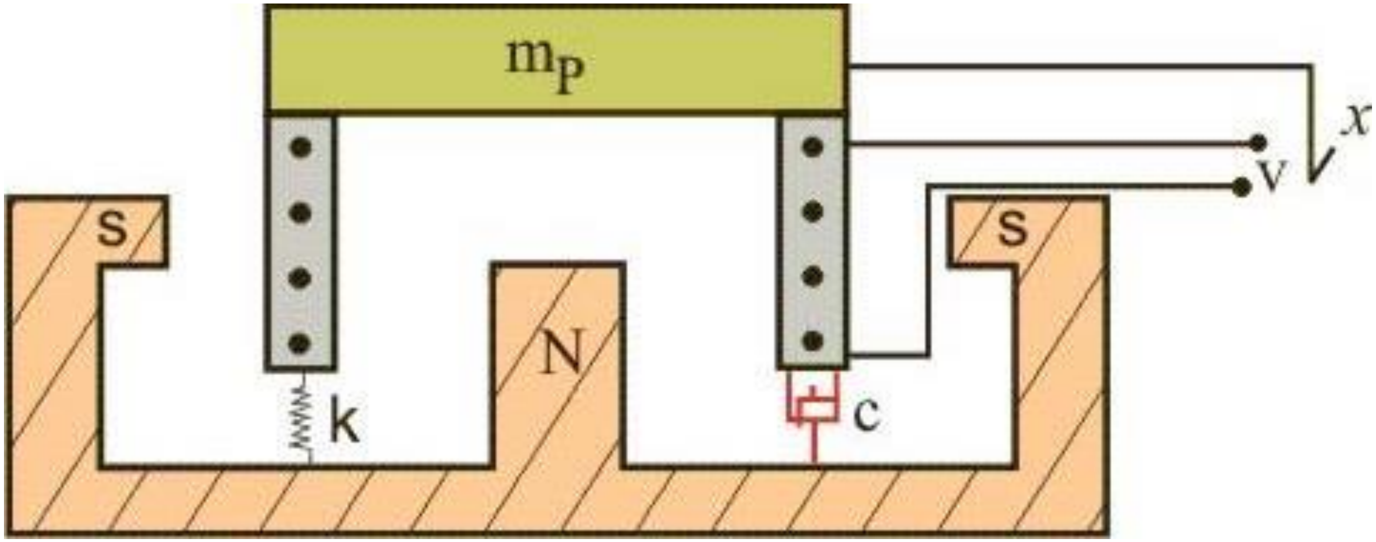


Figure 19.2: Proof mass actuator

A proof mass m_p is connected to a magnetic base with spring k and damper c. The proof mass is placed over a solenoid in which magnetic field could be generated by passing current through coils. The resistance of the coil is R, inductance L, current passing through the coil is i and the proportionality constant corresponding to back EMF is k_b. The EOM are provided below.

Governing equation for electric system

$$Ri + L\frac{di}{dt} = V - k_b \dot{x} \tag{19.4}$$

Governing equation for mechanical system

$$m_p \ddot{x} + k_p x + c_p \dot{x} = k_a i \tag{19.5}$$

where k_a is the current constant

Converting Equation 19.4 into frequency domain,

$$RI + LsI = \bar{V} - k_b sX$$

$$I = \frac{1}{R + L_s}(\bar{V} - k_b sX) \tag{19.6}$$

Similarly, from 19.5

$$s^2 m_p X + k_p X + c_p s X = k_a I$$

$$\left(s^2 m_p + sc_p + k_p\right) X = k_a I$$

Using Equation 19.6 we get

$$\left(s^2 m_p + sc_p + k_p\right) X = \frac{k_a}{R + Ls}(\bar{V} - k_b sX)$$

Denoting, $\frac{1}{\mathrm{R} + \mathrm{L_s}} = \frac{1}{\mathrm{Z(s)}} = \tilde{\mathrm{A}}\,(\mathrm{s})$

$$\left(s^2 m_p + sc_p + s\, k_a\, k_b\, \tilde{A}\,(s) + k_p\right) X = k_a\, \tilde{A}\, \bar{V}$$

$$X = \frac{k_a \tilde{A}}{\left[s^2 m_p + s\left(c_p + k_a k_b \tilde{A}(s)\right) + k_p\right]} \bar{V} \qquad (19.7)$$

Force Exerted by the PFMA

Also, force exerted by the proof mass actuator on the base is $f = -m_p\ddot{x}$, therefore, $F(s) = -s^2 m_p X$.

Using Equation 19.7

$$F = -\frac{m_p s^2 k_a \tilde{A}}{\left[m_p s^2 + \left(c_p + k_a k_b \tilde{A}(s)\right)s + k_p\right]}\bar{V} \qquad (19.8)$$

This relationship tells us how force F will be generated by the proof mass accelerator upon application of voltage $\bar{V}$.

Electro-Hydraulic Actuator for Active Vibration Control

- Passive Neutralizer eliminates primary response only at a particular frequency.
- Use of active element - for example, a hydraulic actuator would increase the advantage of tuned mass damping for a broad frequency range.

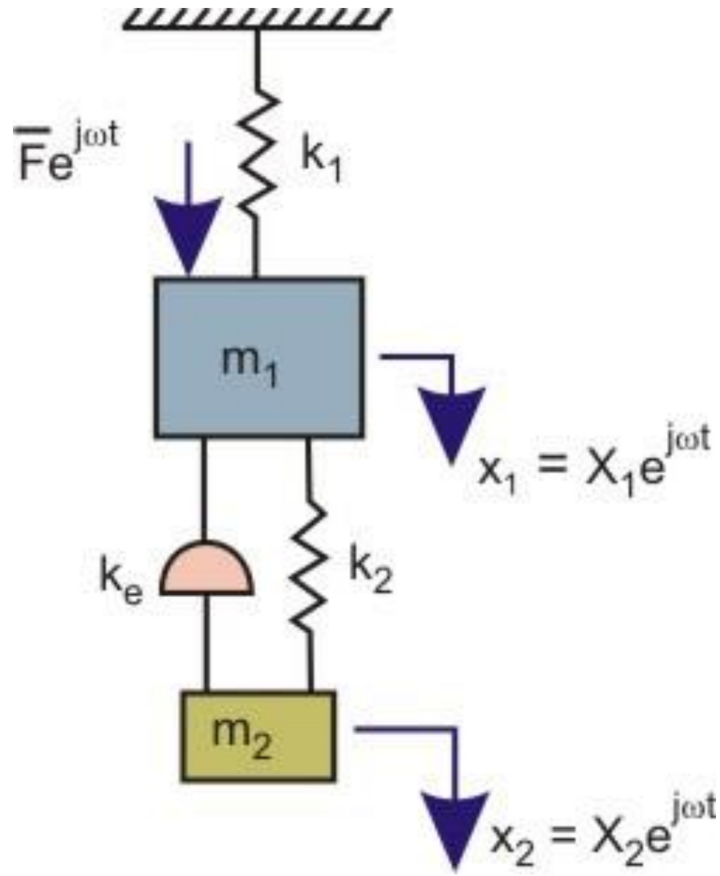


Figure 19.1: Active dynamic vibration absorber

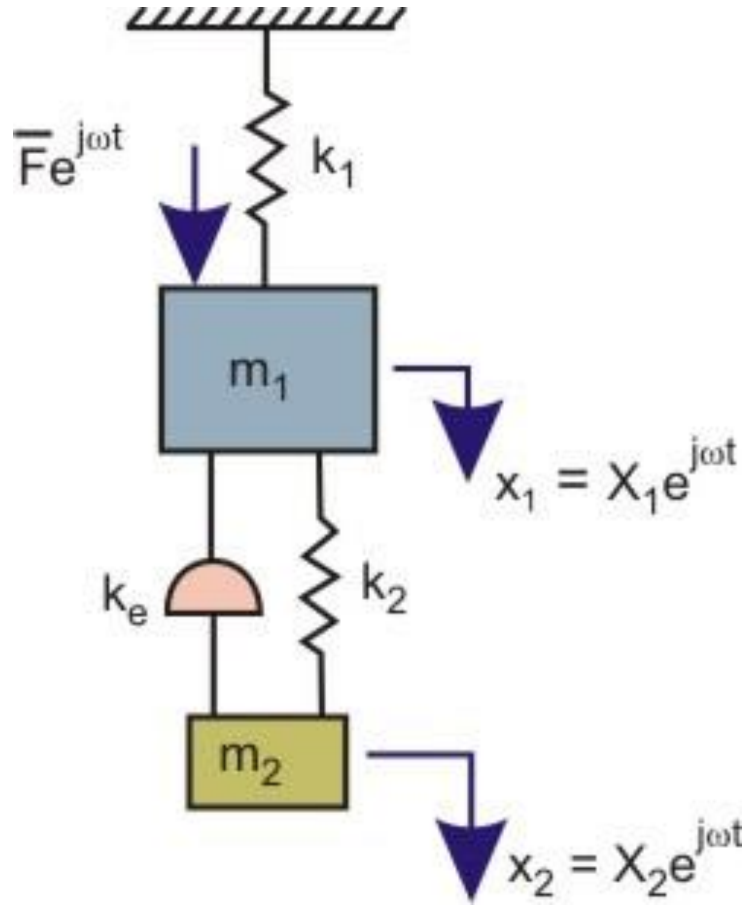


Figure 19.1: Active dynamic vibration absorber

Let us consider the new model as shown in Fig 19.1. Here, m_1 denotes the primary mass and k_1 the primary stiffness. The damping of the primary system is neglected. The system is subjected to a harmonic excitation $\overline{F}e^{jwt}$.

The primary system is attached to a secondary system of fixed mass and stiffness m_2 and k_2 respectively. However, there is an additional spring element with variable stiffness 'k_e' representative of a hydraulic actuator.

The governing EOM of the two DOF system may be written as

$$m_1\,\ddot{x}_1 + k_1\,x_1 + k_2\,(x_1 - x_2) = \bar{F}e^{j\omega t} + k_e\,x_2 \tag{19.1}$$

$$m_2\,\ddot{x}_2 + k_2\,(x_2 - x_1) = k_e\,x_2 \tag{19.2}$$

Using $x_1 = X_1\,e^{j\omega t}, \quad x_2 = X_2\,e^{j\omega t}$

from Equation 19.2 we get

$$-\omega^2\,m_2\,X_2 + k_2(X_2 - X_1) = -\,k_e\,x_2$$

or

$$(k_2 - \omega^2\,m_2 + k_e\,)X_2 = k_2\,X_1$$

or

$$\boxed{X_2 = \frac{k_2}{k_2 - \omega^2 m_2 + k_e} X_1} \tag{19.3}$$

Similarly, from Equation 19.1, we get

$$(k_1 - \omega^2 m_1) X_1 + k_2 (X_1 - X_2) = \bar{F} + k_e X_2$$

or,

$$(k_1 + k_2 - \omega^2 m_1) X_1 - (k_2 + k_e) X_2 = \bar{F}$$

or

$$\left[(k_1 + k_2 - \omega^2 m_1) - \frac{k_2^2 + k_e k_2}{k_2 - \omega^2 m_2 + k_e}\right] X_1 = \bar{F}$$

Thus, when the hydraulic actuator is switched on the active displacement of the primary mass X_{1a} may be written as:

$$X_{1a} = \bar{F} \frac{(k_2 - \omega^2 m_2 + k_e)}{(k_1 + k_2 - \omega^2 m_1)(k_2 + k_e - \omega^2 m_2) - k_2^2 - k_e k_2}$$

When the hydraulic system is switched off, the passive displacement of the primary mass X_{1p} may be written as

$$X_{1p} = \bar{F} \frac{(k_2 - \omega^2 m_2)}{(k_1 + k_2 - \omega^2 m_1)(k_2 - \omega^2 m_2) - k_2^2}$$

$$\frac{X_{1_a}}{X_{1_p}} = \frac{(k_2 + k_e - \omega^2 m_2)}{(k_2 - \omega^2 m_2)} \times \frac{(k_1 + k_2 - \omega^2 m_1)(k_2 - \omega^2 m_2) - k_2^2}{(k_1 + k_2 - \omega^2 m_1)(k_2 + k_e - \omega^2 m_2) - k_2^2 - k_e k_2}$$

For a simple case, use $k_1 = k_2 = k, \quad m_1 = m_2 = m, \quad \omega^2/(k/m) = \Omega^2$

$$\frac{X_{1_a}}{X_{1_p}} = \frac{\left(1 + \frac{k_e}{k} - \Omega^2\right)}{(1 - \Omega^2)} \times \frac{(2 - \Omega^2)(1 - \Omega^2) - 1}{((2 - \Omega^2))\left(1 + \frac{k_e}{k} - \Omega^2\right) - 1 - {}^{k_e}/_{k}}$$

As a test case,

for $\dfrac{k_e}{k} = -2 \quad \dfrac{X_{1_a}}{X_{1_p}} = \left|\dfrac{\Omega^6 - 2\Omega^4 - 2\Omega^2 + 1}{\Omega^6 - 2\Omega^4 + 1}\right|$

and for $\dfrac{k_e}{k} = +2 \quad \dfrac{X_{1_a}}{X_{1_p}} = \left|\dfrac{\Omega^6 - 6\Omega^4 + 10\Omega^2 - 3}{\Omega^6 - 6\Omega^4 + 8\Omega^2 - 3}\right|$

From these expressions, you can check that the negetive feedback system with $k_e/k = -2$ works better for a wider frequency range.