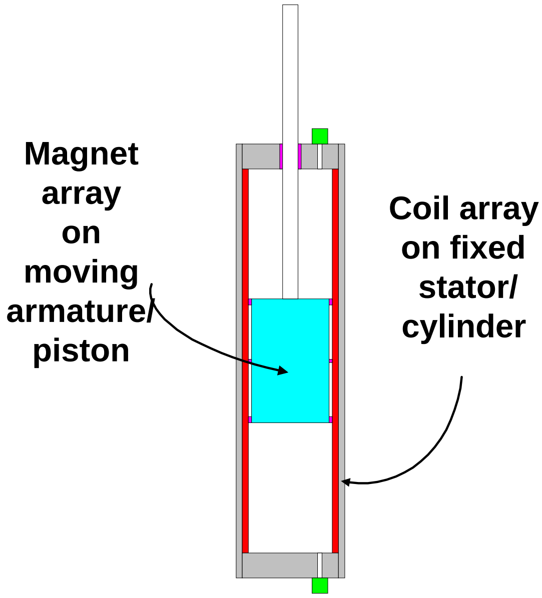
The performance of electromagnetic actuators in motion systems

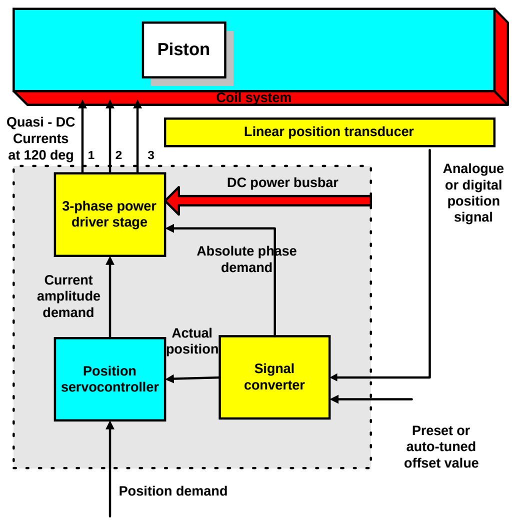
A ServoRam™ electromagnetic actuator provides:-

- Extreme positioning accuracy, independent of load or velocity
- Speeds to 80 metres/second
- Thrusts to at least 100 tonnes
- Strokes to more than 100 metres
- High efficiency – actually increases with speed of movement
- Zero mechanical backlash – force is created at the point of load
- Zero electrical hysteresis
- Zero transport lag
- Control time constant in milliseconds
- Inherent force sensing
- Dual pneumatic/electromagnetic action that minimises power demand
- Fail safe dynamic braking



The ram control system

- Uses an off-the shelf motor drive and menu-driven software.



In its application to motion bases and stabilised platforms the electromagnetic ram technology provides:-

- **A silent, all electronic** system
- No Hydraulics - no mess, no cooling, no pumps or high-pressure pipes
- No ballscrews – no noise, no wear, no windup or slow response
- Inherent force sensing allows body motion interaction
- Simple, wide-tolerance, robust mechanical design
- Fully sealed (waterproof) machinery
- Very low maintenance requirement
- Off-the-shelf power units and controllers

- **Unsurpassable performance** – an order of magnitude better than the best hydraulic system
- Faster, smoother and more precise response
- Self-contained and fully-automatic counterbalancing
- High power efficiency through patented design features

Notes on the frequency response of motion systems

The sinewave motion of an object can be written as

$$x = A*\sin(\omega t + \phi)$$

Where x is the instantaneous position
A is the peak amplitude
ω is the frequency of the motion in radians/second
t is the time with reference to a datum
ϕ is the phase angle at t=0

Any type of motion may be considered to be equivalent to the simultaneous action of a number of sine waves of different amplitudes, frequencies and phase offsets. The precise values of these parameters may be derived by using the well-know Fourier transform. So if we know how the system behaves in response to a single variable frequency, we can predict its behaviour generally.

Transport lag

Conventional (e.g. hydraulic) motion actuators have an upper cutoff frequency that is set by the time required for a valve to move from one flow direction to the reverse. It will be obvious that if it takes 10 milliseconds (say) for the valve spool itself to move from one position to the other, it cannot possibly send fluid backwards and forwards any more rapidly than that! In the example, the cutoff frequency would be 50 Hz. There is absolutely no response at a higher frequency.

Even after the valve has opened, there is another delay caused by the time taken for the whole column of fluid from the tank right through to the piston of the actuator to accelerate from zero or to reverse its direction of flow. In electric ballscrew actuators the equivalent delay is known as “wind-up” as the gears move to take up the load or to reverse its direction.

ServoRam electromagnetic actuators have ZERO transport lag – when the current is in the coil, the force is exerted. There is no upper frequency “cutoff”, just a gradual decay, as explained below.

Velocity

Differentiating the motion equation, we have

$$dx/dt = \omega * A * \cos \omega t$$

where dx/dt is the velocity at any time.

This equation allows us to calculate how the amplitude of any motion is limited by the velocity of the actuator. **(Note that this is a <u>fundamental</u> limitation that is entirely independent of the load on the ram.)**

Electromagnetic rams have a limiting velocity that is set by the motor DC rail voltage and the back-emf produced by the coils. As the speed increases the back-emf reaches the rail voltage and the thrust falls to zero. The real limit is actually less than this, because there is always friction in the system that needs a finite drive current, so the back emf must be less than the rail voltage. If the ram has a limiting speed of Vmax, the amplitude Amax is obviously set by

$$Amax = Vmax/\omega$$

So that the maximum possible amplitude of any motion at frequency ω is inversely proportional to the frequency.

As the frequency doubles the maximum possible amplitude is halved, and so on. This is known as a “3db per octave slope” and the frequency at which the amplitude has fallen to half what it was at very low frequencies is called the 3db point. Obviously, for a ram with a peak velocity of Vmax, the 3db point is reached when

$$Vmax/\omega = A/2$$

For example, for a ram with a stroke of 0.1 metres (A = .05 metres) and a limiting velocity of 1 metre/second, the 3db point is at 40 radians/second (6.4 Hz). At that frequency the maximum possible amplitude has been reduced to .025 metres. At double the frequency (an octave higher) the peak amplitude is halved again, and so on.

Inertia

It will be clear that the more massive a load, the more difficult it is to move it quickly back and forth. In fact the energy required to get it moving increases as the square of the speed. This is reflected in the basic motion equation, which can be differentiated again to give

$$d_2x/dt^2 = -\omega^2 * A * \sin\omega t$$

where d_2x/dt^2 is the acceleration of the load

Suppose that the ram produces a peak thrust of P Newtons and the load has a Mass M kilograms. The peak acceleration is given by

$$(d_2x/dt^2\ )max = P/M$$

We can see from this equation that the maximum amplitude at any frequency is given by

$$Amax = P/(M*\omega^2)$$

And that for every doubling of the frequency the maximum amplitude will be reduced to one quarter of its previous value. This is called a “6db per octave slope”.

For example, if the ram of the previous example generates a peak thrust of 5000 Newtons and sees a reflected mass of one tonne, the maximum amplitude will have fallen to 12.5 mm (one quarter of its maximum) at 20 radians/sec or 3.2 Hz. At 6.4 Hz it will have fallen to only 3.1mm

It will be obvious that as the frequency increases, the amplitude limit set by the inertia of the load quickly dominates the effect of the velocity limitation. The frequency at which it takes over is called the “6db crossover point” and it given by

$$P/(M*\omega^2) = Vmax/\omega$$

So that

$$\omega = P/(M*Vmax)$$

In the case of the example ram the crossover is actually 5 radians/second or 0.8 Hz – meaning that the amplitude falls by 6 db/octave above that frequency.

Performance of real systems

The ServoRam™ is inherently a simple device, with only one moving part and a rigid structure. It behaves in a classical way, so that its measured performance is always in close correspondence with theoretical predictions.

In the same way, motion bases such as the Stewart Platform that are built using such rams act in close accordance with predictions. Because the systems have a well-known geometry - and because they have an irreducible minimum number of moving parts – they follow theory right up to a frequency close to the mechanical resonance.

A special electromagnetic motion base was built in 1996 as a test vehicle for optical stabilising systems. The client took great care to calibrate the behaviour of the machine and his results confirmed its predicted behaviour.

Except for that base, all other electromagnetic motion bases have been built for use in motion simulators. It is completely unnecessary to measure the precise performance of entertainment simulator bases – what matters is how it feels and how reliable it is. There are no statistics on the record concerning the dozen or so bases made to date.

Nevertheless, every Engineer to whom the structure and workings of the ram is disclosed accepts – even without demonstration - our flagship statement that:-

The ServoRam™ is powerful, robust, reliable, versatile, silent, efficient, sensitive, clean, fast and extraordinarily precise. Its performance in motion control cannot be surpassed by any other technology – at any price.