

## A NEW FAMILY OF DUAL-ACTION LINEAR MOTORS

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This presentation describes the origins, development and some recent applications of a new family of linear motors. The machines are based on a very versatile form of three-phase tubular motor that is capable of producing large thrusts and precise movements at high velocities. Because they combine fluid actuator capabilities with electromagnetic forces the motors have proved to be very versatile and highly efficient.

### 1. INTRODUCTION

The Author was previously engaged in the design and development of simulators for the Entertainment business and for the training industry. These machines used hydraulic technology for the motion bases, because only hydraulic rams were capable of applying the large forces that were needed to move several tonnes of mass with the required precision and bandwidth. The associated flow-control valves and electronic control systems for such machines were already highly developed.



Figure 1. 12-seater simulator for entertainment

However, the largest market for entertainment simulators is indoors, where there is a huge demand for personal and twin-seater machines. But severe problems were encountered when scaling down hydraulic systems to operate small interactive simulators indoors, because the various drawbacks of hydraulics made them unacceptable for most locations. Chief amongst the drawbacks was the high power consumption, followed by the fine oil mist that emerged from the actuators over a period of time and settled on carpets, curtains and nearby clothing. Some clients also viewed the oil mist as a fire hazard and some thought that it might be toxic.



Figure 2. Prototype 2-seater interactive simulator

It was therefore essential that an alternative form of actuator was developed to open up the indoor market for simulators of all kinds. Pneumatic rams were unsuitable because of their thermodynamic properties, leading to imprecision and low bandwidth. Ballscrew jacks were also discounted because of their high wear rates, noise levels and general bandwidth limitations.

#### 1.1 Gas Springs

To solve the power consumption problem, the machine deadload was supported on gas (air) springs, so that only friction and inertial forces needed to be produced during the machine motion. The resultant decrease in power demand was dramatic - in the order of 40:1.

It was then clear that the actuators must be driven electromagnetically, since no other method was compatible with the air suspension technology.

## 1.2 Early types of dual-action machine

The cylinder was lined with magnets and the piston of the gas spring actuator was fitted with coils to which electric current was supplied. This led to a piston-cooling problem and so the structure was inverted, with magnets on the piston and coils lining the outer cylinder. The prototype machine produced a thrust of 300 Newtons, but with the help of Lotus Engineering several complete 3-axis motion bases were quickly produced using rams capable of 1500 Newtons peak thrust. Today even a small motion platform uses rams that are capable of 3000 Newtons thrust.



Figure 3. Early ram made by Lotus Engineering

It should be noted that the electromagnetic forces are created in the same piston by which the fluid forces are produced. The machine is simultaneously a fluid ram and an electromagnetic machine.

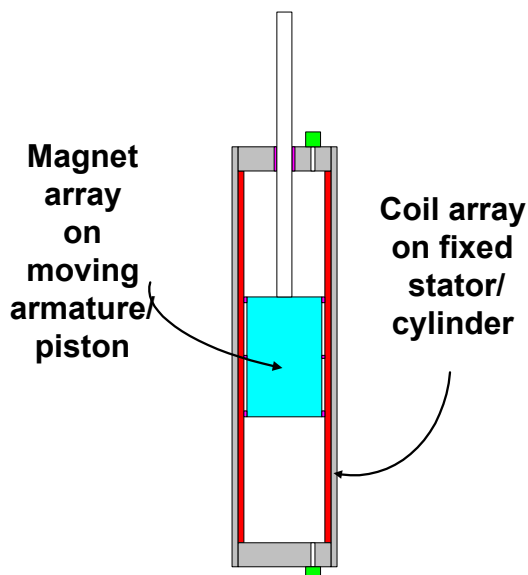


Figure 4. Simple diagram of dual-action ram

## 2. DEVELOPMENT OF THE MOTOR

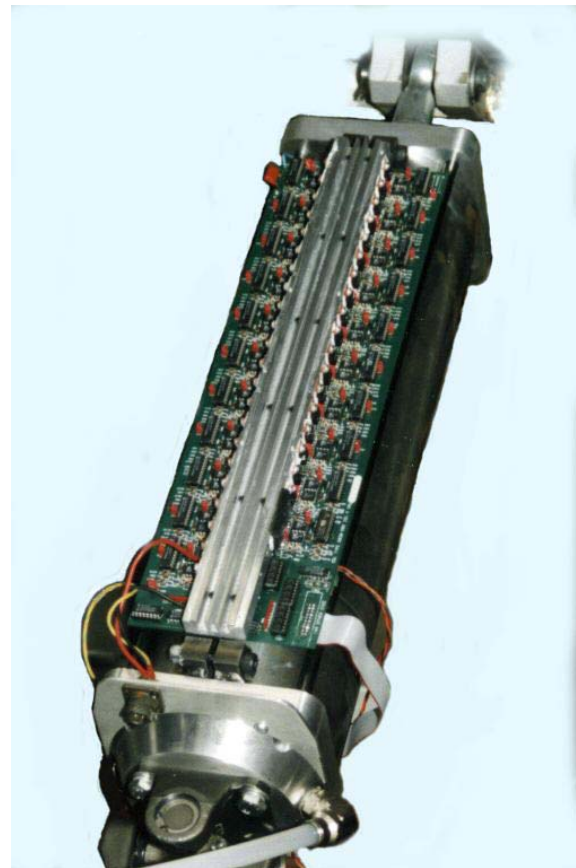


Figure 5. Coil controller mounted on an early ram

### 2.1 The Control System

The prototype and its early successors did not treat the electromagnetic system as an integrated motor, but as an array of individual coils, to which current was supplied in the appropriate sense when the magnetic piston was nearby. Later, the dimensions of the magnetic circuit were modified so that the machine became the true linear equivalent of a 3-phase rotary servomotor, with three power terminals.

The position feedback system was also modified to a cyclic form so that, to an off-the-shelf rotary motor drive unit, the linear motor appears identical to a rotary machine. Thus, many types of industrial drive unit can now be used to control the actuators, whatever their size, thrust and linear stroke.

The following diagram shows the configuration of a control system for a brushless three-phase linear motor of this type.

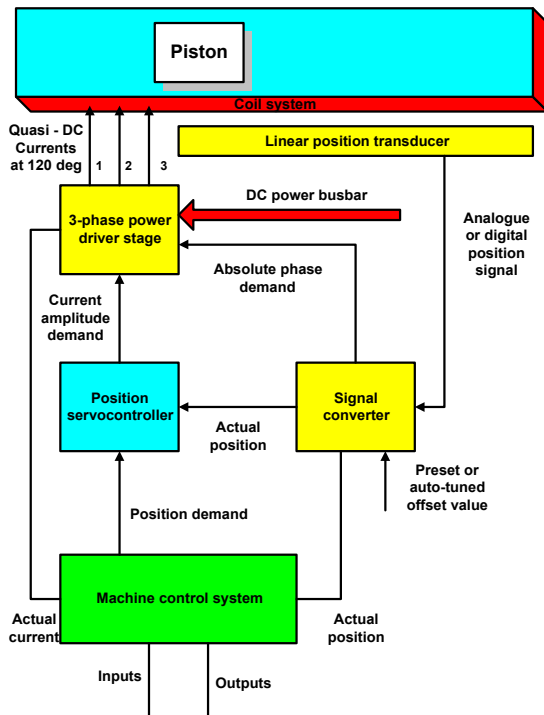


Figure 6. Block schematic of motor control system.

## 2.2 Flux density

Typically, the piston of a dual-action ram consists of a stack of permanent magnet discs, sandwiched between polepieces that direct the flux outwards through the electric coils. The thrust of each element is the cross product of the flux density, the current flowing in the coils and the length of the windings.

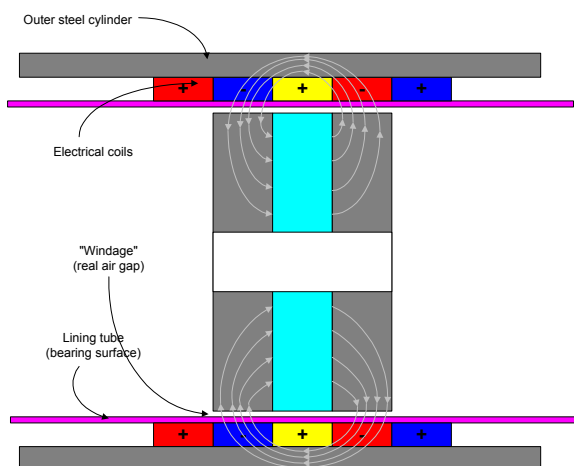


Figure 7. Force element diagram

Thus to produce a certain electromagnetic force it is necessary to use a minimum weight of steel (to carry the magnetic flux) and of copper (to carry the electric current). The values of these minima depend on the design flux density in the coil windings and on the

efficiency with which the heat can be carried away from the coils, which in turn sets the electric current density in the copper. Early designs of the ram were too heavy for some applications and demand increased for higher thrust-to-weight ratios. For rams of conventional design, it was found possible to increase the working flux density in the coils to more than 1.3 Tesla. In another development the electric current density was increased by a copper-in-steel arrangement that also allowed low flux density, low-cost ferrite magnets to be used in a design that produced a working coil flux of 0.6 Tesla in the coils of a very robust and temperature-tolerant machine.

It should be noted that a ram can produce a short-term peak force that may be ten times greater than the force for which it is continuously rated.

## 3. ACTUATOR TOPOLOGIES

The interesting properties of the dual-action electromagnetic ram have now become known to imaginative engineers in a variety of industries worldwide. The various specifications supplied by these engineers have encouraged the technology to evolve into several different topologies. These are described in outline in the following sections.

### 3.1 Double-ended piston-in-cylinder rams

(See Figure 4 above.) In this design, fluid forces can act on either side of the piston. The opposing fluid chambers are usually pre-pressurized and act as gas springs that store and recycle the kinetic energy of a mass in rapid reciprocating motion. The electromagnetic forces superimpose a precise control of speed and position during the machine action.

### 3.2 Single-ended hollow tube machines



Figure 8. Typical single-ended industrial ram

The output element is a hollow thrust tube that passes through a seal ring on the outside of the machine, so that the motor is totally enclosed. In a typical application the thrust tube supports a deadload, which is counterbalanced by the gas-spring that is formed by pressurizing the inside of the device.

### 3.3 Free-piston machines

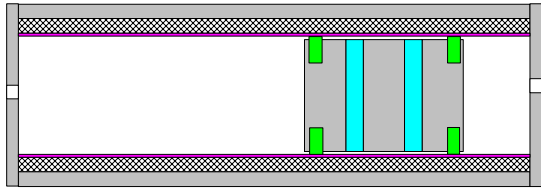


Figure 9. Diagram of free-piston actuator with permanent magnet piston

This topology allows the piston to act directly on a gas contained within the ram, removing the requirement for any external moving seals.

### 3.4 Free-piston impact machines

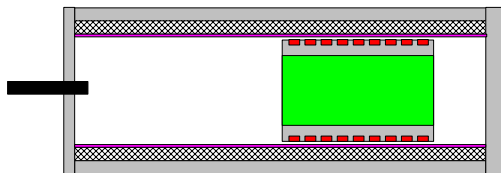


Figure 10. Schematic diagram of controlled-impact hammer motor.

The piston is accelerated along the bore of the machine, to deliver the integrated energy as a precisely-controlled blow to a tool at the end of its travel. Energy is also accumulated in an accelerated return stroke, stored and recycled in a gas spring remote from the tool and delivered as the starting energy of the hammer stroke itself.

### 3.5 Slotted linear machines

There are many applications for the dual-action electromagnetic ram that need a very long stroke length, or which demand that the mechanism fits into a small space. It has proved to be possible to rearrange the elements of the ram into a form in which the piston carries a fin that protrudes through a slot along the length of the machine and carries the force outwards to the machine mechanism. The coil connections can be rearranged to make this possible.

The dual-action properties of the machine are retained, since the technology of strip sealing has already been well developed for slotted pneumatic rams.

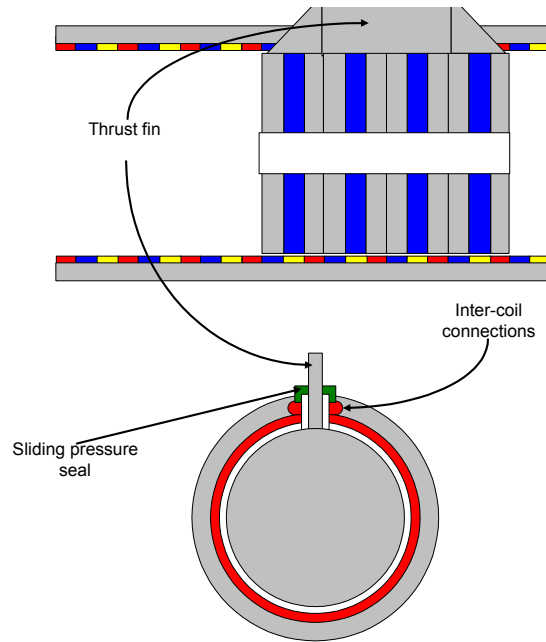
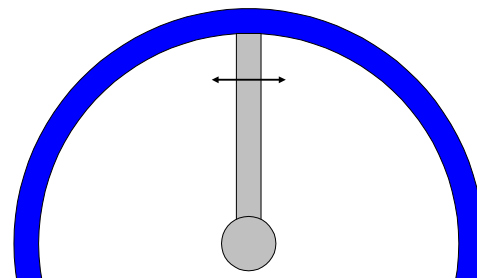


Figure 11. Slotted linear ram.

### 3.6 Slotted toroidal machines



**The slotted ram may be curved into an arc to produce torque via a connecting arm. Either or both chambers may be pressurised to balance deadload forces on the piston**

Figure 12. A slotted ram formed into an arc.

The arc may become a complete circle and the piston length may be extended to fill the whole of the torus, the torque being carried to the central axis of the machine by a disc or a series of spokes.

This produces a special form of precise rotary motor that is capable of generating very high torques directly, without any gearing.

## 4. EXAMPLES OF APPLICATIONS

### 4.1 Flying Shear

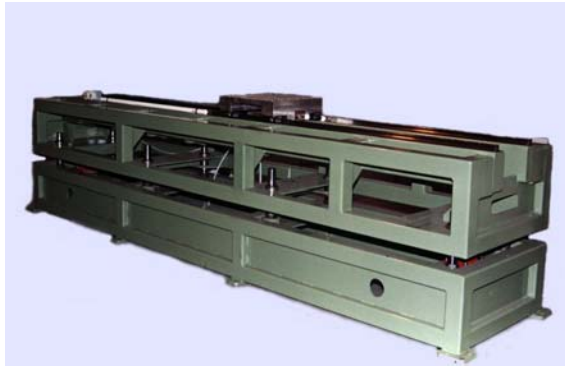


Figure 13. Base for a flying shear.

A typical ram for a flying shear has a thrust of one tonne, a stroke of 1.5 Metres and a peak velocity of 3 metres/second. The mechanism is capable of a dynamic positioning accuracy better than 25 microns. The stator assembly is sealed at both ends and is pressurised on both sides of the piston, so that the machine moves between two springs, into which the kinetic energy of motion is dumped and recovered, for each direction of motion. The spring rates are dynamically adjusted by a control system based on the integral of the electromagnetic drive current. This automatically tunes the system to resonance at its operating frequency and minimises the energy consumption.

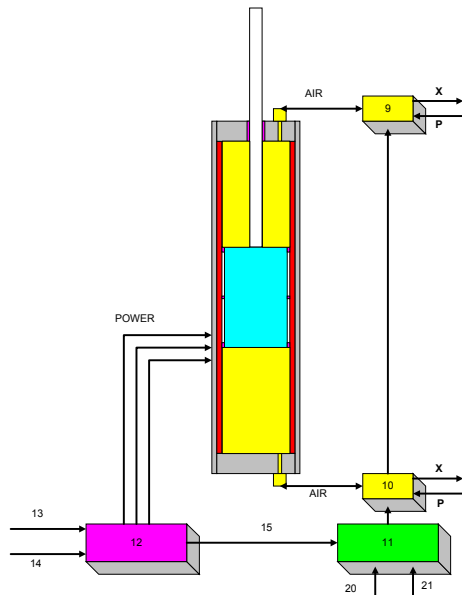


Figure 14. Automatic gas spring tuning arrangement.

### 4.2 Motion base



Figure 15. Six-axis Stewart Platform

A set of six electromagnetic rams forms a silent and clean motion base with a spectacular agility and frequency response. A base of this type is being used by the US Navy for fundamental studies on their requirements in several areas of operation – including under water training. A similar machine is being considered as an agile positioner on an assembly line.

### 4.3 Aircraft Catapult



Figure 16. Catapults and jet blast deflectors.

A slotted ram design may be used for Aircraft Carrier catapults. It is particularly suitable for this application because it can be fully sealed and set beneath the deck in the same way as a steam catapult. Its predicted efficiency is 94% - in contrast to the 6% efficiency of a steam catapult. The catapult ram is designed to produce 1 MegaNewton thrust at more than 80 metres/second and it is 108 Metres long.

#### 4.4 Ship-to-ship Transfer High Point



Figure 17. Typical transfer high point mechanism.

When stores are transferred between ships at sea, the cable is anchored to a mechanism that allows it to be raised and lowered several metres as required to land the goods safely on deck. Existing high point machines use rotary motors and chain belts that require a great deal of maintenance. The British Navy is interested in the use of sealed, dual-action slotted rams to replace these mechanisms.

#### 4.5 Direct-drive Elevators

A vertical arrangement of the slotted ram is also being developed for direct-drive elevators, in which the counterbalancing function is performed by the gas spring within the stator casing. The ram provides a unique safety feature for elevators. Even if the counterbalancing system should fail and the power be disconnected, a load will fall at a terminal velocity of about half a metre a second. This is because the stator coils are automatically shorted out to form a very strong dynamic brake. These machines are too expensive for commercial use, but in fighting ships they have the advantage that the elevator need not be confined to straight-line vertical motion, so that it can be used to transfer ordnance from a secure storage location.

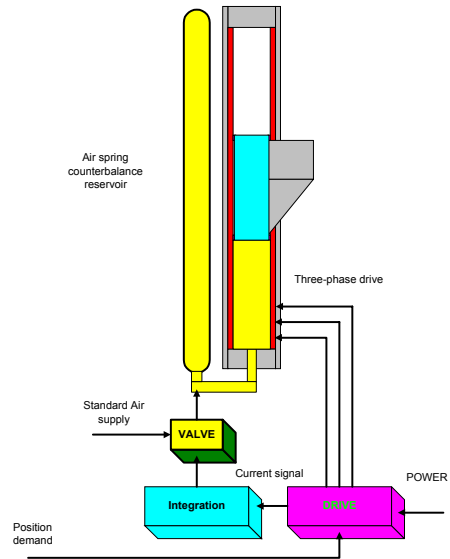


Figure 18. Direct -drive elevator system.

#### 4.6 Gas processing

(See figure 9) The ram may be used as a power transfer element in a chemical process – without any external rod or thrust tube. In this application the piston moving within the cylinder may be used to move or to compress fluid – or to control the rate of expansion of a gas. The energy released by the expansion of the gas is directly transformed into electrical energy that is conveyed to another part of the process.

#### 4.7 Torque motor



Figure 19. Hydraulic steering gear mechanism.

Conventional ship's steering gear is powered by a complex arrangement of linear hydraulic rams that turn cranks. For a number of reasons, it would be an advantage to replace this by a rapid-action high torque mechanism with only one moving part. The toroidal form of the slotted ram is capable of at least 3 MegaNewton metres torque and it is now being considered by suppliers to the US and British Navies.

#### 4.8 Vehicle suspensions

One of the most interesting applications of the technology is in car suspension systems. Consider a vehicle with gas spring suspension, in which a superimposed, instantly-adaptive electromagnetic force cancels out the friction forces and the thermodynamic effects of the gas spring. Newton's first Law says that, since there is then no change in the vertical force acting on the vehicle, it will continue in smooth straight-line horizontal motion. That is the basis of the dual-action electromagnetic ram suspension.

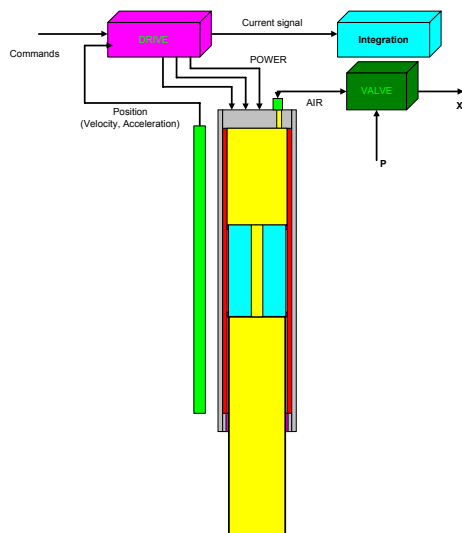


Figure 20. Vehicle suspension ram

Figure 21 shows the equivalence diagram of a dual-action ram, placed between the wheel axle and the wheel point of a vehicle. A perfectly acting gas spring would decouple from the vehicle all the forces from the wheel that would have disturbed its vertical position. However, the gas spring rate is finite, the system has mass and the spring is bypassed by the friction of the piston bearings and seals. The gas spring does transfer a portion of the wheel forces to the vehicle.

In the wide-bandwidth electromagnetic suspension system the electromagnetic forces are superimposed to compensate for these imperfections so as to keep the total force transferred to the wheel point at a constant value. The desired value of this vertical force is continuously changed as required to cope with braking and inertial turning forces, under the control of a wheel point accelerometer.

Because the position of the piston is always known, the unit is also capable of automatic control of ride height to a manually-set datum or in response to ride experience.

As previously explained, the pressure in the air spring suspension unit is continuously and automatically controlled, in accordance with the electrical power demands of the ram.

In passive mode, the active suspension elements act as electrical generators – as variable dampers, converting vertical wheel motion into power that is fed back into the electrical system of the vehicle.

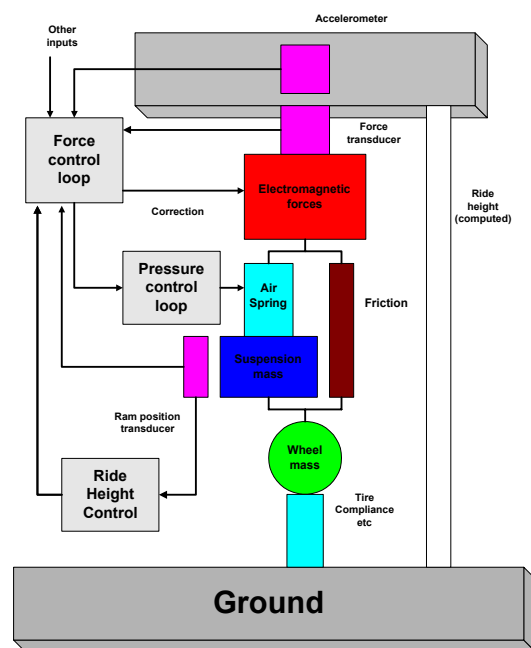


Figure 21. Complete suspension system

#### 5. CONCLUSIONS

The piston-in-cylinder, tubular construction of a three-phase brushless linear motor is remarkably useful in a wide variety of applications.

Significant power savings can be made by the dual action of the piston as a fluid system component, which allows a great flexibility of control.