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"Electromagnetic rams - a better way to move things about?"

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Phillip Denne has specialised in new product design in a variety of industries for more than 40 years. He is the author of more than 100 patents, from pollution controls and milk weighing systems to microwave transponders – and electromagnetic rams. He is an entrepreneur, having started ten companies from scratch, and he now practices as a design consultant.

Why develop a new form of linear electric motor?

Denne is called "the father of the entertainment simulator business" because in 1985 he set up a company that designed and built the Super X "Venturer", the world's most popular entertainment simulator machine. More than 400 of these machines were sold into 35 different countries. They used hydraulic rams because only hydraulic servo systems were capable of producing the crisp and vigorous movements that were necessary for a convincing and exciting simulation experience.

The Venturer is a 14-seater machine that operates in museums and other large buildings, or outdoors at many seasonal sites. But the largest market for entertainment simulation is for small machines that must be operated indoors, in heated, air-conditioned, carpeted and furnished multi-storey buildings. Hydraulic equipment is incompatible with this market because of the strong shock-loadings that it can apply to the structure of the building and because a fine oil mist emerges from the equipment and gradually coats all the surrounding surfaces of the room. The obvious alternative - the electric ballscrew actuator – lacks the crisp action of a hydraulic ram and it tends to wear quickly, becoming noisy and distracting.

The design breakthrough

A study of the energy exchanges in a simulator motion base led to the idea of supporting the payload on gas springs to remove the deadload and to recycle the kinetic energy of the motion, greatly reducing the power needed for its operation. The problem was then to transfer force to a "floating" object - and it was obvious that only electromagnetic coupling could be used. So the piston of each gas spring was modified so that it became the armature of a linear motor, the electrical coils of the machine also being contained within the ram cylinder.

During a long period of development, the magnetic circuit of the ram was improved until it became the true linear equivalent of a very efficient rotary machine – the three-phase brushless servomotor. The linear action of the ram could then be controlled by one of many standard *rotary* motor electronic drive units that have been developed for industrial use.

The electronic drive unit was also programmed to tune the gas spring subsystem at frequent intervals, so as to minimise the electrical power consumption of the ram. Automatic adjustment makes the machine tolerant of small leaks, of temperature changes and of changes in load characteristics.

Different topologies of the electromagnetic ram

It was soon realised that the technology had many industrial uses and that designing different types or topologies of electromagnetic ram would help its application to those markets. The first rams were double-acting piston-in-cylinder machines, but it proved to be useful also to make a single-acting (hollow piston rod) design. Some applications did not need a piston rod to convey the force out of the cylinder but instead used the free piston as an inertial reactance, or to process chemical fluids within the cylinder. Another design produced the energy-integrating electromagnetic piston that can be used to deliver a precise blow to a tool, for example.

There is also a series of slotted rams, in which the piston carries a fin that protrudes through a slot along the full length of the cylinder. Clearly, such designs allow the ram to have a very long travel without the problems that would arise from the buckling of a conventional piston rod. Even slotted cylinder electromagnetic rams may still have a dual action (combined gas spring) design, because the technology of strip seals for slotted rams has been well developed by manufacturers of pneumatic rams. Slotted cylinder rams may be constructed in an arc – and even in an irregular arc if the electromagnetic piston is constructed with some angular compliance. At the limits of this topology, the slotted ram may be curved into a complete circle to form a very high torque rotary motor.

Ideal control characteristics

The electromagnetic ram has properties that are a control engineer's dream.

- It is a force generator, not a positioner.
- The electromagnetic force is an instantaneous function of the current in the coils.
- There is no mechanical hysteresis or "wind-up" because the armature is rigidly connected to the output element.

- There is no electrical hysteresis, so that one microamp flowing through the coils in one direction produces an exactly equal and opposite force to one microamp flowing in the in the opposite direction.
- There is no transport lag – no valves to move, no fluid to flow. As soon as the current is in the coil, the force is felt at the piston.
- The rate at which the current can grow in the coil is very high, since the time constant is measured in milliseconds.
- The current: force transfer function is absolutely linear and the machine is inherently capable of producing a peak force that is many times the mean force for which it is continuously rated.

The machine has the intriguing property that it can measure the force exerted upon it, because the electronic drive must continuously adjust the current supplied to the ram so as to balance that force to hold any commanded position. This feature was demonstrated in an award-winning machine called the "Virtual Surfer" in 1995. The rider of a virtual surfboard on a simple motion base had only to shift his centre of mass to change the forces in the rams and this in turn modified the motion of the virtual surfboard.

Electromagnetic design

It should be noted that the machine is a classical electromagnetic force generator that operates according to Fleming's Left Hand Rule for the force on a wire in a magnetic field. The force on the coil – and the reaction force on the magnet - is the cross product of the flux density, the wire length and the current in the wire. The operation of the machine should not be thought of in terms of magnetic forces. All the magnetic forces in the machine (which are very large!) are at right angles to the motion. They are accurately balanced out and do not contribute to the thrust.

The early prototype machines used radial magnets on the stator and coils on the armature, but since it was difficult to remove the heat from the piston inside the machine the configuration was altered so that the coils were part of the fixed stator and the radial magnets were fitted to the armature or piston. To increase the flux density in the coils (and thus to increase the machine efficiency) the shape of the magnets was changed to a disc or flat ring, the flat faces being the poles of the magnets. The magnet disc was then sandwiched between two mild steel disc polepieces that turned the flux radially outwards so as to intersect the coils surrounding the piston.

Although the rams were then capable of producing very large thrusts, the machines suffered from a series of problems relating to the control of the current in the coils. At first, the coils were all individually controlled. Although this was power-efficient the system was difficult to make, intolerant of its environment and very jerky in its motion. Modern rams – being the linear equivalents of rotary

three-phase servomotors - have just three power terminal connections. The force elements of the armature are all identical, so that adding more elements to the piston simply increases the thrust of a ram of any diameter. The electric coil system may be constructed in ironless form, or as a copper-in-iron machine or as an induction motor. Diagrams show such arrangements.

The advantage of the dual-action property of the design is particularly clear in a double-acting ram for a flying shear application. In this machine the kinetic energy of the reciprocating inertial load is stored and returned to the system twice in every cycle, first from one spring and then from the other. Each gas springs is automatically tuned by an algorithm related to the current consumption which has the effect of making the system resonant at its operating frequency, thus saving a very large amount of energy. A cooling subsystem is no longer needed.

The distinguishing features and the performance advantages of the ServoRam™

There are many designs of linear motor and it may not be obvious what is so different about this new machine. The following features are especially notable: -

- The machine is a dual-action device, combining electromagnetic and pneumatic forces applied simultaneously to the same machine part
- The ram is fully-enclosed and may be hermetically sealed
- The armature (piston) bears directly against the stator (cylinder) via simple self-aligning bearings (piston rings)
- There are no extraneous magnetic or electrical fields
- The topology of the magnetic circuit makes it very efficient
- Most versions of the machine can be used at any angle and that angle may change violently during operation

As a result of the features described above, the machine is: -

- Scaleable. From 10 Newtons to 1 MegaNewton
  From 10 mm to a few Km
- Very precise Better than a micron
- Very fast Better than 100 m/sec
- Wide bandwidth Better than 100 Hz
- Highly efficient Better than 90%
- Temperature tolerant -200°C to +200°C
- Simple to make. Reliable. Silent. Clean. Watertight. Versatile.

Examples of military applications

- The rams were used to build a high-performance dynamic test rig that subjects periscope optical equipment to precise movements in six degrees of freedom simultaneously.
- A high-performance six-axis Stewart Platform is used by the US Navy to study new simulators for helicopters and for high-speed attack craft. This uses internalized gas springs that are continuously tuned to optimise power consumption.
- Both the UK and US Navies are studying the application of large rams to the replacement of hydraulic actuators in submarines.
- Large slotted rams are under consideration for aircraft catapults in UK and US aircraft carriers. The machines must accelerate a 30-tonne aircraft up to a speed of 75 metres/sec in 2.8 seconds in a distance of a little over 100 metres. The peak delivered power must be 80 Megawatts.

The advantages of a linear motor over the steam catapult are that: -

- The force is continuously and precisely controlled during the launch and that the peak force applied to the aircraft is very much less. That extends the operational life of the aircraft and may even allow Air Force machines to use carriers without any special strengthening of the airframe.
- The ship's space required for the support subsystems is a fraction of that previously required and there is very little noise from the high-reliability electromagnetic drive.
- The calculated efficiency is at least 95%, which should be compared to the 6% of a steam catapult.
- The associated manual workload is much reduced because the machine is self-monitoring in its operation and the motor can be made to run in reverse in order to return the shuttle to the start point.
- Regenerative braking systems will recover the kinetic energy of the piston mass, which for a steam catapult is jettisoned in a water brake.

- Aircraft elevators of the present design are each powered by one of the largest hydraulic rams I have seen so far. The elevators lift 180 tonnes 15 metres in 10 seconds – the delivered power is almost 3 Megawatts! None of the energy is recycled and there is no counterbalancing system. To produce the same action with much greater efficiency and operating redundancy, a battery of electromagnetic rams may be used in future ship designs.
- There are many internal elevators in a fighting ship, used for the transfer of goods and ordnance throughout the vessel. Their replacement by electromagnetic devices is also being considered, together with the many actuators that operate armoured doors at each deck level.
- Jet blast deflectors are heavy water-cooled plates that are raised behind an aircraft immediately prior to launch. These use hydraulic rams that the Navy wants to replace with simpler and more reliable devices.
- Actuators are used on the decks of fighting ships to transfer stores from one to the other whilst traveling together at sea. The cable that is run between the ships is anchored to a "moveable high point" that is raised during

the transfer and lowered to place the stores onto the receiving deck. Existing mechanisms are often chain driven and quickly become inoperable under the wet and corrosive conditions of the ship's deck. The sealed and counterbalanced electromagnetic ram with only one moving part is now being considered as a replacement.

- Ships steering gear presently consists of a set of hydraulic pumps, tanks and cooling systems driving a battery of rams in a crank mechanism. It should be possible to replace this complex assembly by a direct action super torque motor – another type of electromagnetic ram. This is actually a slotted ram curled around the steering shaft. Machines of that type can be designed to produce peak torques of more than 3 Megatonne-metres.

Suspension systems

Electromagnetic dampers and electromagnetic active suspensions are being considered for cars, railway carriages, armoured fighting vehicles and high-speed marine craft. The military are also considering their use in stabilised platforms for missile launchers, guns and laser equipment.

The principle of a dual-action electromagnetic suspension is very different from an existing suspension system and is based on Newton's First Law, which says that a body will naturally remain stationary or follow a straight-line course. A force must act on the body in order to disturb it - so the objective of a high performance suspension unit or stabiliser mechanism must be to isolate the body from external forces. That is how the new systems work.

The gas spring part of the dual-action electromagnetic ram is used to provide first-order isolation and the spurious friction and thermodynamic forces that still remain are simply nulled to zero by the electromagnetic part of the ram. Schematic equivalent diagrams of a vehicle suspension are provided by way of illustration. A number of dual-action electromagnetic rams are now being evaluated in Detroit and elsewhere.

Other industrial applications

It will be obvious that such a versatile machine has many industrial uses. These are not described in detail, perhaps being well known to many, but they include: -

- Virtual cams
- Flying shear drives
- Weaving machinery
- Packaging machinery
- Automation and robotics
- Metal forming
- Food processing machinery

- Precision machining centres
- Vibration and other materials testing
- Door, vent and valve positioners
- Soil fluidisers, pile drivers
- Pantograph mechanisms
- Three-dimensional conveyor drives
- Hammers and other impulse machines

Elevators

The rams are under intensive study for the replacement of hydraulic and rotary electric mechanisms in elevators within civil structures. Particularly attractive to this market are the simplicity of the design, its silence and smooth, jerk-free action and its ideal safety characteristics. When the power fails the coils of the system are automatically shorted out, so that the ram acts as a powerful dynamic brake. Even if there was a simultaneous failure of the counterbalancing system, the ram may be designed to limit the terminal velocity of a fully-loaded lift car to just a fraction of a metre per second.

The electromagnetic ram excels

- Where fast, precise and variable-speed motion is needed
- Where simplicity and reliability are paramount
- Where contamination is unacceptable
- Where silence is essential
- Where the environmental conditions are severe
- Where the load inertia is high
- Where the peak-to-mean force requirement is great
- Where the load may be counterbalanced and kinetic energy can be recycled

Every news item about the ServoRam™ produces an avalanche of enquiries from all over the world, from clients who want to replace their existing fluid systems by simple “solid state” electromagnetic devices – **and some of those companies now make fluid actuators.**