“The PemRam™ - an electromagnetic linear actuator”

P.R.M. Denne
Denne Developments, Bournemouth, England.

Summary.

The ***PemRam™*** was originally designed to replace hydraulics in vehicle simulators. Previously, only high-pressure fluid actuators could provide the bandwidth and precision that was needed for accurate motion simulation but they could not be used in confined spaces close to the general public. Hydraulic actuators are also inefficient when they are used in simulators, so that even a small machine had to use a three-phase power outlet. These disadvantages were blocking access to a very large market for small simulators.

We have developed a range of electromagnetic actuators that combine the properties of a DC motor with those of a pneumatic ram. In a motion base the pneumatic piston forms part of a gas-spring assembly that supports the simulator capsule at any height and attitude and the new technology exceeds the performance of hydraulic machines.

The ***PemRam™*** has a number of unique properties that have applications in other markets.

The Compelling Power Of Motion

It may be helpful to begin by saying something about the motion of a simulator.

Nobody drives, or flies, or moves in any way, by using visual information as the primary sensation for control. If you think about it, you will realise that you use your eyes to set targets for your actions but you control movement by feel. You feel the road through the steering wheel, you feel the seat acting on your body, the snow beneath your skis, the lift beneath the wings of your aircraft or the ground beneath your feet. You respond to these sensations instantly and instinctively; you respond subconsciously, without rational thought.

That is because human beings have been trying to stand upright for a million years or so; we have learned to program balancing skills as fast reactions to external forces. These forces are felt as pressures on the skin - and the skin is the largest and most primitive organ of the body. It has the most deeply-rooted connections to the human brain. **Communicate with a human being through the skin and you trigger primal, powerful, emotional responses.**

The key element of simulation - which makes it very different from a cinema, TV or videogame experience - is the motion system. Motion has a powerful and gripping effect; it adds energy and excitement to the visual experience. This is because the sensations of movement go through the skin directly to the subconscious and instinctive parts of the brain. The provoked responses are irresistible and they force the person to concentrate intensively on the visuals of the experience. The participant is driven to act as though the visual scenes are real - whatever their visual quality - and as though life itself might depend upon the outcome. Full hormonal responses are triggered and the Virtual Experience becomes an emotional one. That is why entertainment simulators are so popular - and why personal, home-based simulators will be so attractive and so important as vehicles for creative entertainment software.

Hydraulic Motion Systems.

Until now every good simulator has used a mechanism that relies on hydraulic rams to move the cabin (or "capsule") about. Hydraulic rams are expensive, precisely-machined steel pistons driven by oil under high pressure. But until now only hydraulics technology, pushed to its limits, could provide the accuracy and fast response necessary to create the right sensations of movement. Only hydraulics was good enough to satisfy the exacting demands of the military and civil training business. The leisure industry also used hydraulics for its own motion simulators, such as those in the major theme parks.

A strong demand now exists to bring small (one or two seat) motion simulators into entertainment arcades and to bring personal simulators into the home. But hydraulic motion systems waste huge amounts of power and get hot. They need frequent careful maintenance and, inevitably, they leak oil, or spray it as a mist over their surroundings. There is sometimes a fire risk and possibly a toxic danger. Hydraulic technology is only acceptable for the entertainment industry if the mechanism is outdoors or is not close to the public and if it receives regular skilled maintenance. Something very different is needed for arcade machines and for use in the home environment. Designers have tried without success to solve the problem using two obvious alternatives:-

- **Pneumatics.** This technology uses air at 6 bar instead of oil at 100 Bar and small leaks are not a problem, but the thermodynamics of a gas present fundamental difficulties. Pneumatic actuators do not work for simulation because their response is too slow (a mass of air has to be moved even to change the force - the ram has to be inflated or deflated to alter the pressure, which takes time) and because they have a transient imprecision (the air is compressible; it bounces).

- **Electric jacks.** These have been used in small "arcade-quality" motion systems for many years and more recently they have been used in a number of larger machines. Unfortunately, they have a significant number of moving parts; using rotary motors, belts and speed-reduction gears to drive nuts that exert forces on threaded shafts via ball or roller bearings . Because they rely on hard metal surfaces under high contact pressures their operating life is limited by wear and noise, which has given them a bad reputation in the "bums on seats" business. There is also a significant delay arising from the inertia of the mechanism, because the motor and gears have to "spin-up" or "spin-down" to reverse direction; this prevents a ballscrew motion base from reproducing "surface feel" or crisp, transient events.

Wipe-outs and Energy consumption

Motion systems work properly only when the person in the capsule cannot see the outside world at all. He/she must be totally enclosed and relate only to the visual image on the display screen. The motion system then provides **accelerations** which are locked to the edges of the movements shown on the video screen. The human brain does the rest by being convinced that each short acceleration is extended into the large movements which are shown on the video screen. In fact the mechanism is programmed to "wipe-out" - to slow down, reverse direction and return imperceptibly to the straight-and-level starting position.

It is important to note that the movements of the simulation capsule are not simply related to the movements of the "vehicle" which is being simulated. Just because the aircraft in the simulation is pitched up it does not follow that the capsule is pitched up and just because the motor cycle in the simulation is banked hard around a bend it does not follow that the simulation capsule is also banked in the same way. Knowing what the motions of the simulation capsule have to be to produce the most exciting effects on the occupant is one of the secrets of the business!

A simulator capsule does not actually go anywhere but always returns to the same position. Logically, therefore, it is possible to save most of the energy. That is to say, whatever energy is pumped into the capsule in order to get it moving can be taken back again a few seconds later because the capsule is then slowed down and brought back to its original position. No long-term change takes place in the kinetic or potential energy of a simulator. All the energy that is used goes in overcoming friction.

We have therefore patented a technique by which the simulator is supported on gas springs, arranged in such a way that it is accurately counterbalanced at any position and attitude. The actuators then need to handle a pure inertial load. They expend no energy in supporting the deadload against gravity.

Efficiency improvements from Counterbalancing.

A typical motion base for a simulator will move the payload about 0.5 metres in any direction and will attain a velocity of about 0.5 metres/second, corresponding to an acceleration of 0.5g applied for 0.1 seconds. It is **the acceleration** that is the essence of the experience for the occupants - neither the velocity nor the displacement can be perceived from within the enclosed simulator capsule. (Similar parameters apply for the rotational motions, which in a synergistic mechanism are generated by the same rams and which are therefore compatible with their linear movements).

The energy required to move a mass M a vertical distance h is given by

$$E_p = M g h$$

If the same mass M is accelerated to a velocity v, the energy required is given by

$$E_k = 0.5 M v^2$$

So that the ratio of the gravitational energy changes to the inertial energy changes of the system is

$$gh / 0.5v^2$$

This is about 40 for a typical simulator, whatever the load. If the simulator is supported by a gas-spring counterbalance the energy that is actually used to provide a ride experience will only be **2.5%** of that used otherwise. (Of course there are frictional losses, copper losses and other inefficiencies that degrade the effect, but there is, nevertheless, a startling improvement in energy demand using this patented method of construction.) A simulator weighing more than a tonne will operate from a single-phase mains socket.

Piston-and-cylinder actuators.

Since the forces must be coupled to a “floating” mass the actuators have to be electromagnetic. No other actuator will do the job. Because no electromagnetic actuators were available to the required specification in 1991, we have had to develop them from scratch ourselves.

About twenty years ago Professor Laithwaite did a lot of work on three-phase linear induction motors. He used to say that a linear actuator was a sort of electric motor which had been sliced down to the centre of the armature shaft, and spread out flat. Power applied to the motor then caused the flattened armature to move across the surface of the flattened stator in one direction or the other. Electromagnetic actuators of approximately this form have been used to drive magnetically-levitated trains and to position industrial transfer mechanisms, for example. Unfortunately, the machines are not very compact or efficient in a simulator application, the electromagnetic field “leaks” quite badly.

Since we had started with the concept of a gas spring we were already thinking in terms of cylinders. In conceiving the ***PemRam™*** what we did, in effect, was to take the long edges of Laithwaite’s flattened electric motor and bring them round in the orthogonal direction to form a cylinder. We did the same with the armature and then put the armature shaft down through the centre of the cylinder to act as a piston rod.

The piston is sealed to the inside of the coil assembly to form part of a gas spring and the machine looks just like a pneumatic or hydraulic actuator.

In principle, these topological transformations can be applied to any sort of electric motor, DC, AC, Universal, Variable-reluctance, Stepping, Moving-coil, Moving-magnet, or whatever. For the simulator application we have concentrated first on the DC machine in moving-magnet configuration and we are now developing other versions for industrial use.

The Construction of a PemRam™

The ram consists of a piston carrying an air seal, moving within a polished cylinder that is separated from the outer steel case by a series of coils that are concentric with the piston. The piston (armature) carries an array of magnets that produce radial magnetic fields. The magnetic fields intersect a number of the coils of the machine stator, depending on the instantaneous position of the ram piston. Current to those coils is controlled in amplitude and polarity by pairs of pulse-width-modulated transistors that are mounted on the outside of the ram along its length. The ram operates from a 350 Volts or +/- 175 Volts DC supply rail with local energy storage, buffered from the AC mains supply.

Other types of PemRam™

It is sometimes more appropriate to design the actuator to be a moving-coil machine, especially when the stroke is more than a metre or so. In this case we make special arrangements to cool the armature, which, unlike a rotating device, cannot be cooled by the motion of the machine itself.

You will perhaps appreciate that a moving-coil induction-motor version of the ***PemRam™*** is simpler to make but somewhat less efficient than a permanent-magnet machine.

It is also possible to construct a variable-reluctance ***PemRam™*** and to produce a version that uses a permanent-magnet armature to form a stepping ram, with the useful property that it will resist displacement when the power is turned off.

Performance characteristics

1. Thrust

- In 1993 we demonstrated the counterbalance system and a single moving-coil ram that produced a peak thrust of 300 Newtons, using off-the -shelf ferrite magnet elements.

- In 1994 we were shipping 3-axis motion bases for 300 Kg loads that used moving-magnet (Nd-Fe-B) rams rated at 1000 Newtons peak thrust. (Peak duration approx. 0.1 seconds every ten seconds or so.)

- At present we are making a range of motion bases rated from 850 Kg (3-axis) to 3500 Kg (six-axis) that use rams with peak thrusts from 2000 Newtons to 9800 Newtons. (Same peak : mean diversity)

- For other applications we have in design rams that produce a steady thrust of 7500 Newtons with a stroke of six metres and others that produce a force of 50 Newtons with a stroke of two centimetres.

2. Velocity

- The simulator application does not normally need a velocity greater than 0.5 metres/second at full thrust and the limiting velocity of our motion base actuators is designed to be 1 metre/second.

- We have built a batch of rams having a velocity of 2 metres/second for a special application and we believe that more than 5 metres/second is attainable. (The stalled thrust of a high-velocity ram must, of course, be very carefully controlled.)

- It should be noted that, in contrast to fluid actuators, the efficiency of a *PemRam™* increases with velocity. It is a force-generator.

3. Acceleration

- The acceleration achieved by the ram is determined by the mass and inertia of the load to which it is connected, so it is rather difficult to comment. However, an instrumented motion base has demonstrated accelerations of several “g” - well above the limits of sustained human comfort!

- The people who know that they are sitting on an air cushion - on soft gas springs - and that there is no hard physical connection between the free pistons of the rams and the outside world are always startled by the hardness of the ride on a ***PemRam™*** motion base. People who are not astronauts do not think of themselves as inertial objects. There is no general human awareness of the difference between $E_p = Mgh$ and $E_k = 0.5Mv^2$!

4. Jerk (rate of change of acceleration)

- This is where the ***PemRam™*** really scores, since there is only one moving part in the system - the piston itself, acting directly on the load. The computer output signal, transformed into an electric current and amplified, is itself the cause of the force generated by the ram. There is no transport lag for valves to open, for pressure to build up or for fluid to flow. There is no intrinsic inertia in other moving parts.

- The electromagnetic circuit of a typical ram has a control time constant of about one millisecond. When the current is flowing in the coil, the force is already acting on the piston.

- In addition to his surprise at the power of the electromagnetic actuator to move him about, we find that the speed with which the force is applied - the Jerk of the actuator - also convinces the rider that he is using a “hard”, fast and very-powerful machine. 0.3 g applied in a millisecond feels like more than 1g applied in 20 or 30 milliseconds.

5. Size and Weight

- The rams are subject to the usual constraints of electromagnetic machine design, in addition to which they cannot be geared-up in any convenient way.

- To generate a large thrust they need physical size - that is, the thrust is proportional to the volume of the piston (although the piston may be hollow).

- The force is produced as a B.I.L. product, which means that it needs plenty of soft steel for the “B” and plenty of copper for the “I.L.” There are no lightweight high-performance electromagnetic materials!

- Typical ram weights at this stage of development are 35 Kg for a 150 mm diameter 2000 Newton machine with a stroke of 240 mm and 150 Kg for a 200 mm diameter 9800 Newton machine with a stroke of 500 mm.

Useful features of the actuator.

Silence. This is especially important where a human being is trying to concentrate or to listen to a sound track. In the simulation business, because hydraulic and ballscrew actuators are noisy, the silence of the ***PemRams™*** produces an immediate impression of better quality. Like a Lexus car, perhaps.

Simplicity and reliability. Nothing moves except the ram. Nothing wears except two bearings and one air seal.

Wide operating tolerances. There is no requirement for micron filtration or white-glove maintenance.

High transient capability. There is no hard limit to the transient thrust capability of the ram over a short time interval - but the electrical power used by a stalled ram increases as the square of the thrust.

Speed of response. This is an order of magnitude better than a high-quality hydraulic device.

Power regeneration. Using the ram in driven mode, the machine operates as a generator - a controllable damper with an electrical power output that may be returned to the electrical supply system.

Ease of control. Thrust is strictly a linear function of drive current, which may be made the controlled parameter and which is independent of the position of the piston. There is no time delay between current flow and output thrust.

"Virtual Surfing". (Human body-motion sensing)

The ***PemRam™*** is a force-generator, not a movement-generator like the hydraulic ram. That is to say, the rams on a motion base produce exactly the right amount of force to hold the simulator in any required position. The force is directly proportional to the coil current, which, being within the position control loop, is always known. Suppose that the simulation is of a surf-rider, for example. When the surfer moves, the weight distribution on the simulator changes and the forces produced by the rams automatically adjust to compensate. The new current values can be fed into the computer running the virtual vehicle dynamics, so that the surfer's motion is altered just as it would be in reality.

For the first time, therefore, it is possible to simulate travel that is controlled by the natural and instinctive movements of the human body. This is an important and exciting development for serious training and for entertainment simulations that have a sports theme. The "Virtual Surfer" has become a recognised logo of my company!

Some Applications Of The *Pem*RAM™.

Civil Engineering.

Many passenger lifts in buildings up to five storeys high are raised by hydraulic rams. ***PemRam™*** actuators, several metres long, can replace the hydraulic rams with an efficient, silent, clean and much more reliable product - that might eventually be made for a price low enough for general private housing. Some of the largest companies in the lift business have approached us and we expect to demonstrate lift rams next year.

Automobile Suspensions.

We have been asked by several makers of luxury cars to consider the use of ***Pem*RAM™** in active suspension systems. Studies show that the new linear motor has several advantages in this market. Not only can it do the active suspension job, but the same device, acting as a damper, can vary its characteristics under computer control in milliseconds if required. That is, a ***Pem*RAM™** suspension system can be tuned for every road condition as it is encountered. What is more the energy absorbed by the damper (sometimes 300 Watts a wheel) is not thrown away as heat but is fed back into the battery supply, saving fuel. Simultaneously, the piston of the ***Pem*RAM™** can act as part of a self-levelling, height-adjusting fluid spring system. We are progressing contacts with EEC, US and Japanese car makers.

Rail Coach Suspensions.

Mathematical studies carried out by Loughborough University as part of an EEC programme show that the ideal suspension for a rail vehicle is an electromagnetic one. Parallel studies in association with two major European companies show that the necessary forces, displacements and power levels are within the reach of ***Pem*RAM™** technology. DDL is negotiating a framework for the co-operative development of a prototype rail coach suspension.

Industrial Automation.

The advantages of cleanliness, silence, high peak thrust, unlimited speed, intrinsic force-sensing, reliability and wide control bandwidth mean that the ***Pem*RAM™** has many factory applications. For example, the rams can replace hydraulics in food and drug manufacture, where contamination would be very expensive. In high-speed machinery such as that for sorting, transferring and packing goods, the unique ability of the ***Pem*RAM™** to "freewheel" when handling inertial loads saves a great deal of energy.

Although vent actuators only operate at infrequent intervals and their first cost must be low, they are often placed in almost inaccessible positions, so maintenance is very expensive and reliability is vital. The ***PemRam™*** has only one moving part - the piston itself. This makes it intrinsically reliable and we have been approached by a leading European company to produce simplified, low-cost rams stepping rams to move valves and vents.

Security.

The power needed to operate a ***Pem*RAM™** can be stored in a small space - for a year or so in a battery or for several minutes in a charged capacitor. This means that the device can be self-contained, so that it may be used to carry out a security action in a no-power emergency. We are in discussion with a British company concerning a ***Pem*RAM™** device to drive a security screen into position faster than a robber can pull the trigger of a gun.

Stabilised Platforms.

When optical devices like cameras or measuring equipment have to be mobile on a land or sea surface they need to be isolated from disturbances when they are in use. This is also true for guns, radar antennae and missile launchers. The complex and expensive servosystems previously employed have used powerful motors, gears and cranks to generate the movements that are necessary. Such “hard” mechanisms might now be replaced by the simpler, counterbalanced and efficient ***Pem*****RAM™**.

Cross-country vehicle seating.

Human beings need stabilisation to avoid fatigue and injury when driving vehicles such as earth-moving equipment across rough terrain. Although soft springing has been used, a significant improvement would result from the use of ***Pem*****RAM™** actuators that combine an airspring and position stabilising function. We are in discussion with a major European manufacturer of earth-moving equipment.

Pile Driving.

As a result of earlier studies by a British consultant, it seems to be feasible to use both the fast rise-time and the intrinsic feedback properties of the ***PemRam™*** in a novel form of high-speed pile-driver.

Bulldozing, Planing and Ploughing

Similar considerations are now being applied to reduce the mechanical forces used in earth-moving equipment of various kinds.

The ***Cyberseat™***

The largest market for simulation is in the home. The ***PemRam™*** technology can be applied in an interesting way to produce an exciting consumer product - a home simulator seat that can be plugged into a computer to bring a videogame to life. The **Cyberseat™** actually connects a human body to a computer - and therefore to the Internet - providing a new way for people to communicate remotely. The seat may also be used for massage and to “feel” musical rhythms, perhaps as part of a relaxation routine. *It can even be designed to sense the body motions of its occupant, providing a two-way human interface to the Internet.*

We regard the **Cyberseat™** as potentially our most profitable product development during the next few years: the company is already in contact with a number of manufacturers and distributors. Entirely new software will be needed to run the **Cyberseat™** interface to a computer system and to provide imaginative videogames and other applications. The product is expected to be released in quantity during 1997.

Luxury aircraft seating

The ***Pem*****RAM™** application to home simulators can also be extended to luxury aircraft seating. This is because the technology can be applied in reverse - to hold a passenger steady against outside disturbance, thus providing an extremely cushioned ride. We are now seeking partners for the development of a flight-safety-approved product.

The ***PemRam™*** actuator is a patented piston-in cylinder machine that uses the latest magnetic materials, high-frequency PWM technology and microprocessor control to build a silent, fast and precise actuator which has many applications in industry.

March 29th 1994