Motion Platforms or Motion Seats?

Eur. Ing. Phillip Denne

Synopsis

Motion cues are essential in simulation because research shows that driving – or flying – requires an instinctive connection between the human body and the mechanics of the vehicle. Good motion cues are essential if the trainee is to learn this connection correctly. It follows that poor quality motion systems actually have a negative training effect. It has often been argued that no motion at all is better – and cheaper - than bad motion.

Motion platforms have evolved from that for the Link Trainer to the high-performance 6 DOF mechanisms now used for flight training certification. But they are large, inefficient, noisy and expensive - and it is, in any case, impossible for some types of sustained acceleration to be simulated by motion platforms. Pressure pad motion seats ("g seats") were therefore developed to provide cues of sustained acceleration for high-performance military aircraft. But the original g seat design had a significant latency and this was not corrected, so the machines have generally fallen into disuse.

New types of all-electric motion systems have been developed to overcome the problems of the older motion base and motion seat technologies. Remarkable improvements in performance, reliability and value can now be achieved. Silent, non-pneumatic g seats may be constructed with near zero latency, allowing improvements of training quality in many different areas of application.

The enclosed-capsule simulator with a motion platform is the most appropriate design when a number of persons must be trained to act as a team in a moving vehicle - of any type. Nevertheless, there are limitations to the realism to which continuous vibration (e.g. helicopters) or frequent shocks (e.g. high speed boats) can be applied without causing real damage to the simulator! The seat motion cueing system is more appropriate when the simulator must be small, lightweight and use the minimum of electrical power – or where vibration and shock cues are vital to the learning process. Seat motion systems may be added to large enclosed capsule machines.

A moving platform simulator generally requires the visual system to be carried on the motion base, but this is impractical for an all-round view, such as that required for driver training or aerial combat. VR headsets have a distracting weight and inertia that makes them unsuitable for experienced trainees but in combination with a motion seat they provide a compact simulator system. For ground vehicles, moving only the cab in relation to the stationary screen is quite effective, but large lateral displacements should be provided. A seat motion cueing system works on a different principle and therefore has significant advantages in a "stationary displays" simulator.

Biographical Notes

Eur. Ing. Phillip Denne B.Sc. C.Eng. C.Phys. F.I.E.E. F.R.I. is a British Scientist and Engineer with more than 40 years' innovative experience across a wide range of industries from dairy farming to electronic warfare. He is the author of more than fifty patents and has set up ten new companies from scratch to exploit his innovative technologies. He is probably best known for his work on entertainments simulators since 1985, which has led to the development of the dual-action electromagnetic ram. Denne operates as a design consultant via Guilden Ltd.

In 1979 Denne was commissioned to design and build a versatile EW training facility at the headquarters of Marconi at Stanmore in the UK. The £8 Million TEMPEST complex contained a unique high-performance cylindrical anechoic chamber that became operational during 1983. To demonstrate its real-time microwave scenarios to non-expert VIPs, Denne used computer graphics to aid visualisation – putting the viewer on the nose of a missile that was being jammed, for example. The entertainment effect of this technique encouraged Denne to leave Marconi and to launch a company that developed the Super X "Venturer" leisure-industry simulator that is now marketed by Camber Entertainment Ltd.

MOTION PLATFORMS OR MOTION SEATS?

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SIMULATOR MOTION CUES

No one drives - or flies – by vision alone; the trained reaction to motion cues has been found to be much more important. That is why motion simulation is an essential part of a training or amusement experience.

Careful studies show that a human being engaged in vehicle guidance control responds first to tactile disturbance and only later to visual field disturbance. This is thought to be due to the experiences of early life, which teach balancing skills as fast reactions to external forces on the body. The human quickly learns to update the model of its motion and to predict his/her future position. To walk upright as we do, we have to react very quickly and so the control system has evolved without any delay in an interposed, consciously-accessible reasoning process. We learn how to react and we repeat successful strategies of movement. It appears that we use a similar subconscious and pre-programmed reactions to exert forces on other objects; which is why we can play ball games that would otherwise require impossibly fast and precise calculation.

When we take control of a vehicle - surface, air or space - we bring with us our fast reactions to body forces and we use them to gain mastery of the vehicle. We learn instinctively how to blend with the vehicle - to feel that it is a natural extension of our body. We rapidly build an intuitive understanding of where the edges of the vehicle are and what is happening to them. By using the controls to move the vehicle and learning the results we also gain an ability to predict the future position of the craft - and when it is moving we learn how it interacts with the surrounding medium (land, sea, or air).

We say that a vehicle is under control when it "feels right" - when the driver is able to make the vehicle feel as he/she wishes, whether in response to input commands or against disturbances from the outside environment. We do not give the visual experience the same level of importance as our tactile experience in our assessment of security in the vehicle. This is because what we feel is the complex sum of accelerations that are integrated over time to produce velocities and further integrated to result in displacements. The displacements alter the visual field, but the changes are perceptible later than the body sensations. I am sure that many of us have had the electrifying experience of losing control of a car on an icy surface, even for a second. Visually, almost nothing happens - the event is felt - and control can often be regained before a passenger knows anything about it.

I have quoted vehicle control as an example of how important sensations of force - of acceleration - are to us in our daily lives and how we use the instinctive responses of the human body to control machines and other devices we have created. The most important aspect of this brain function is that motion sensations go directly to the subconscious. There is no analytical conscious thought between sensory input and trained or instinctive response. All the appropriate body chemical responses are triggered.

The essence of simulation is that it should be a compelling fantasy. That is, during the progress of the simulation it must appear to be "real" at that instant, even if you are able to reason that it wasn't actually real when you think about it afterwards.

If you have never experienced good simulation then I can assure you that you will be very surprised just how compelling it can be. Thorough simulation is capable of disconnecting you thoroughly from the real world and immersing your mind firmly within a Virtual World. Simulators, whether for serious training or for fun, are machines that are designed to create a convincing illusion. Simulators do not attempt to create a copy of anything real. They simulate, not emulate. They trick the human psyche by a combination of visual, aural and motion cues - all of which are false.

As I have previously explained, many of the effects on you are induced subconsciously; they go directly to the part of your brain over which you have no immediate control. Even if you are intellectually aware of how the simulator is designed and how it is achieving these disturbing effects, it is extremely difficult to stand back and observe yourself objectively in such a situation. The temptation is to concentrate on all the action in this virtual environment and to get on with the task of flying or driving the simulated vehicle. What dominates the thought process is your interaction with the Virtual

Machine. The stress that is placed on you by your natural urge to compete and even to "survive" does not make you want to get out of the simulation - it actually compels you to go further in. This useful but illogical effect has been observed for many years in professional training simulators.

Stress, especially stress from motion cues, increases the psychological "grip" of a simulation on the participant. Because motion is always involved in the most exciting real experiences, and because motion cues have such a powerful and irresistible effect, a simulation without them is a rather weak, intellectual experience. With good motion cues it becomes a truly emotional experience, in which all the appropriate body hormone releases are triggered. That is why a motion system is such a vital part of a vehicle simulator.

SENSING MOTION CUES

It is incorrect to believe that only the balance organs in the ears are used to sense motion. The human body judges acceleration through skin pressures, as forces acting on it to change its position. That is, the human brain learns to calculate acceleration vectors from the nature of the forces acting on the skin. It learns early in life that a small acceleration acting for a long time will produce the same result as a larger acceleration acting for a shorter time, and it learns to make accurate predictions.

The body in its natural environment continuously experiences a significant acceleration (1g) that produces a large velocity in a short time. The brain spends many months of its early life learning how to manage the effects of this force! Then it has to learn to put the steady gravitational acceleration into the background of its consciousness whilst it stays sensitive to anything that changes. In effect, the brain contrives to have a built-in “wipe-out” or high-pass filter superimposed on its calculations of body acceleration. The time constant of the wipe-out filter is just a few seconds.

There is also a “learned bias of assessment” that estimates the strength of an accelerating force as being greater if it is more rapidly applied. That is, a force that would produce an acceleration of 1g is assessed at more than 1g if it is applied very suddenly. The force is judged to be “more powerful” because if it is applied more quickly it seems to come from a harder surface with less compliance - it is likely to be more difficult to resist. Thus acceleration is deduced from perceived hardness, which is why the “g seat” principle works.

For similar reasons there is a human threshold sensitivity on minor variations of acceleration. The brain learns that nothing bad is likely to happen to the body if an external disturbance only causes a change to its velocity at a rate that is less than 0.05g. A human being is therefore predisposed to ignore an acceleration or deceleration below 0.05 g.

It is just these natural characteristics of human perception that make it possible for a simulator to create its illusion. A motion simulator capsule moves to and fro a small distance (in the order of a metre) at a low speed (about a metre a second) with a safe acceleration (usually less than 1g). Nevertheless, the motion cues can greatly alarm an occupant, who may be convinced that he/she is moving great distances at more than Mach 1 and that he/she has been subjected to large accelerations.

THE TWO TYPES OF MOTION CUE.

There are two sources of disturbance associated with the movement of a vehicle and both must be generated in a simulator to capture the mind of the human towards whom the simulation is directed. The most obvious disturbances result from the control actions of the driver or pilot of the vehicle. A turn to the left, for example, will result in an inertial force to the right that should be felt convincingly by the human involved. Pulling back the aircraft joystick will cause an upward acceleration, and so on. The force is a predictable result of the action by the occupant of the simulator and depends on the dynamics of the vehicle. Such forces are vehicle control interactions; they happen after control is applied and they confirm its correct result.

The second type of motion disturbance results from the interactions between the vehicle and a change in its environment - a bump in the road, a loss of wheel grip, a wave impact in a boat, air turbulence or contact with the runway surface in the case of an aeroplane. The occupant of an interactive simulator has to learn to react to such motion cues. The forces are experienced before corrective control action is applied. In a passive simulator - in which the occupant has no control and is subjected to a pre-programmed illusion - the “changing environment” cues are very important because they generate a powerful conviction that the simulator is free-moving and is not fixed to the floor.

In an interactive simulator the first type of motion disturbance is precisely calculated from the dynamics of the vehicle and the coefficients of the controls. The second type of motion cue is usually generated from a random variation in the coefficient of interaction between the dynamics of the vehicle and the parameters of the data base that describe the surface with which the vehicle interacts. The two families of motion cue are then superimposed.

THE TWO TYPES OF ACCELERATION

In an enclosed environment (such as a simulator cabin) it is impossible to tell the difference between gravitational and inertial accelerations. Gravitational accelerations are caused by the attraction of a large mass nearby - in our case, the Earth - whilst inertial accelerations are produced when we speed up or slow down or turn corners.

This equivalence of accelerations is used as one of the tricks of simulation, so that they can be interchanged continuously to deceive the occupants of the machine. For example, to convince the occupant of a simulator that he/she is accelerating forwards, the capsule can be tipped backwards (so that the Earth’s gravity is felt on the back). Meanwhile the screen visuals show forwards movement and the appropriate sound effects are provided.

Surge (inertial) acceleration is thus simulated by coupling into the (gravitational) pull of the Earth. Because the occupant is in an enclosed cabin there is no visible horizon, so he/she does not know his/her angle to the vertical, and the trick works. In the same way sideways (sway, inertial) acceleration can be simulated by a roll movement - and centrifugal force can be simulated by a combining pitch and roll to couple into the gravitational vector.

THE LIMITATIONS OF MOTION BASES

A motion base consists of a fixed part – usually bolted to the floor – and a part that can be moved through a small distance (about a metre) or rotated through a small angle (30 degrees or so). The movement of one part of the base relative to the other is produced by extendible rams or “jacks”

A motion base is classified according to the number of degrees of freedom in which it can move, up to a maximum of six. (Three linear translations; heave, surge and sway and three rotations; pitch, roll and yaw) It is also classified according to whether the motions can be carried out independently (“stacked”) or whether motion in one degree of freedom automatically limits motion of other kinds (“synergistic”).

Synergistic bases have a number of advantages and they are more commonly used. The Stewart platform, a popular form of synergistic motion base with six degrees of freedom, is used in almost every serious training simulator. But motion platforms of every type have a number of limitations.

In order to produce controlled motion of the required precision and smoothness – and with forces capable of moving masses of up to twenty tonnes – hydraulic rams have been the only possible mechanism. But hydraulic rams are extremely inefficient in this application, wasting more than 95% of the input power, so that the simulator’s electricity demands are high. The mechanism has to be supported by large cooling facilities and there is a significant level of noise.

Hydraulic equipment requires a great deal of skilled maintenance and there are concerns about bringing hydraulic machinery into an environment where it may be close to the general public. The gradual spread of a fine oil mist from the working parts damages any surrounding fabrics and may be a fire risk.

Perhaps the most fundamental limitation of motion base cueing systems is that it is only lateral accelerations that can be presented to the occupant as long-duration cues. The long acceleration effect is achieved by tilting the capsule sideways or tipping it up or down, which couples the local gravitational field into the senses of the occupant as an apparent surge or sway acceleration of up to 0.5g. This can be sustained for many seconds if necessary

But all other acceleration cues are extremely short, because every ram must always remain within the limits of the ram travel length. If the acceleration continues for more than just a fraction of a second a ram piston will approach the limits of its travel and will have to be stopped abruptly. The sudden reverse acceleration does not match the visuals and it completely destroys the illusion of continued motion that must be presented to the trainee.

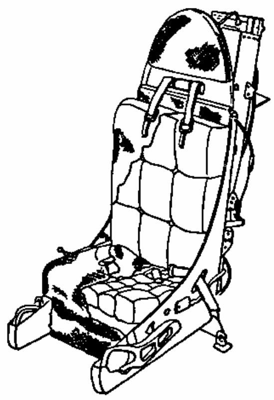
However, it is often necessary to train persons to fly aircraft that are capable of – and must use in normal operation – accelerations of several g for many seconds. It will be obvious that no motion base using rams can possibly generate the appropriate motion cues.

MOTION SEATS

A different technology has therefore been developed to provide the illusion of sustained acceleration.

We have explained that motion is most strongly sensed, not by the balance organs in the head but by the pressures acting on the surfaces of the skin. Any thing that moves the body has to push against the skin surface – and the place where that pressure occurs then feels harder than the other areas of skin contact. The greater the force exerted, the greater the increase in hardness of the area of contact, so changes in hardness are always associated with accelerations and may be used to estimate them. It is therefore possible to create a convincing sensation of motion by varying the hardness of areas of the body with which the body is in contact. That is the basis of the "g seat" mechanism.

"G seats" using pressure pad cues were first developed for use in military aircraft but their construction was expensive and they were noisy.



The design was based on the use of an inflated cushion element that controlled the degree to which a person came into contact with a firm underlying surface – thus varying the apparent hardness of the skin contact. But because it was necessary to physically inflate and deflate the pad – to move air in and out - there was an associated time delay or "latency".

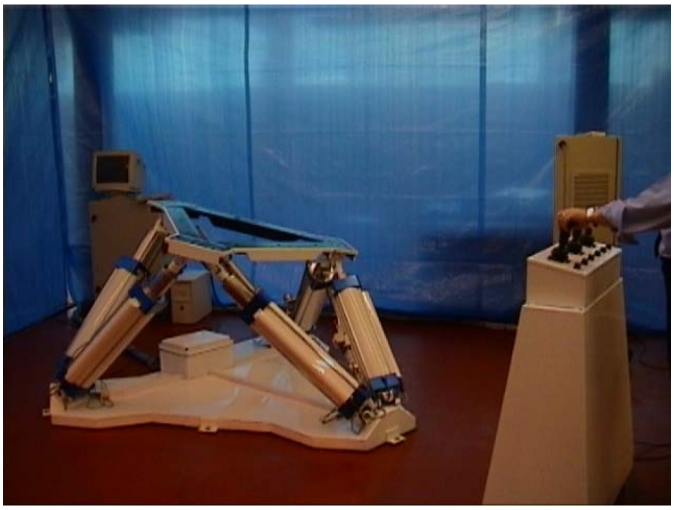
The first effect of the latency was that the motion cues arrived too late to be convincing. The second effect arose from the small subconscious movements that human beings make at frequent intervals to maintain circulation. The pressure pads reacted to the body movements – but a fraction of a second later. Because the human was never aware of its own original subconscious movement, the seat itself seemed to be "alive" and unreal.

MOTION BASE DEVELOPMENTS

During recent years several serious attempts have been made to replace the hydraulic rams in simulator motion bases with electrical actuators.

The earliest attempts used ballscrew machines. These use a rotary electric motor and a gearing system to apply a high torque to a nut through which a screw is threaded. The nut is prevented from moving axially and the screw is prevented from rotating. Thus the threaded rod is extended or retracted by the rotation of the nut. Although the nut carries recirculating balls and the screw has deep, rounded channels to increase the line of contact, the machine has to employ very high metal-to-metal pressures that cause rapid wear and a rise in noise levels. There are many moving parts in the machine and the cumulative deflections of these parts cause "wind-up" - or mechanical hysteresis and time delay. Ballscrew actuators therefore have a limited bandwidth and cannot respond quickly enough for accurate simulation.

Another method of replacing hydraulics with electrical actuators applies the geared, high-torque rotary action to a crank, to which a push-rod is attached. (Smaller versions of these machines have been used for a long time as control loaders.) Although geared cranks are quieter than ballscrew machines, their chief disadvantage is that they produce large off-axis torques of several types. Like ballscrew machines, they suffer from mechanical "wind-up" and bandwidth limitations.



A completely different method uses electromagnetic rams, in the form of dual-action linear motors in which a piston moves freely in a cylinder like a hydraulic ram. In this case, however, the piston is also part of a gas spring that carries the simulator deadload. The piston is constructed from an array of magnets and it is capable of producing very large electrical forces with a short rise time.

The motion fidelity of machines using this technology is an order of magnitude better than that of the very best hydraulic motion bases, with none of their disadvantages. In each actuator there is only one moving part – the piston and thrust rod – so that it is intrinsically reliable, silent and clean.

MOTION SEAT DEVELOPMENTS

Progress in the design of seat simulators has followed a rather similar course. In the early 80's the guru of the g seat – Kron, working with Singer Link in the USA – finally reached the conclusion that for the illusion to work properly, there must also be real motion of the seat pan itself. To produce this motion he used pneumatic actuators - but of course the seat pan motion then suffered from the same latency problems as the seat pads themselves.

A few years later, DRA Bedford (UK) tried replacing the seat actuators with hydraulics. Although the change from pneumatics removed the latency inherent in such mechanisms, it transferred to the small machine the power, leakage and maintenance problems that were the disadvantages of the larger motion base systems. Recently therefore, DRA Bedford has replaced the hydraulics with rotary electric actuators and a product based on that mechanism is available from Cranfield Technologies.

Meanwhile, a US entrepreneur created a large entertainment market for motion seats in an entertainment "Odyssey" project that was proposed for Salt Lake City. The unusual demand triggered a new design of simulator seat that was labeled the "CyberSeat" by the Sunday Times in the UK. Although the Salt Lake City project did not go ahead, a great deal was learned from the associated study work and a very low-cost and lightweight motion seat can now be constructed for consumer applications.

A test rig was constructed for use by the Manned Flight Simulation Unit of the US Navy in its early work on wide-bandwidth motion seat systems for Helicopter training. The test rig uses miniature dual-action electromagnetic rams to provide the seat pan motions and the result is a simple, silent and very powerful machine with a bandwidth approaching 100 Hz. It is capable of reproducing accurately the vibration environment of a helicopter.

THE CHOICE OF MOTION SYSTEM

Because the motion cues represent an intuitive connection with the motion of the vehicle, it is very important for them to be generated with an accurate time relationship to the action of the controls and a good model of the dynamics of the real vehicle. Motion cues that are late, or that result from spurious couplings or resonances of the mechanism, are worse than useless because they teach the wrong intuition. If a trainee actually persists in such circumstances and learns to accept incorrect cues as "normal" the training is negative: reality itself will feel very wrong.

I have several friends who are Formula 1 and Formula 3 racing drivers. They blanche visibly when they try to ride a crude arcade "driving simulator" and they get out hastily. They say that the entertainment machines feel dangerous to them. I am sure the same thing must apply to experienced pilots who ride a simulator with incorrect motion cues – or one without any cues at all.

LOW-COST MOTION BASES.

Several markets for training simulators will not accommodate the size, weight, cost and complexity of a full 6-axis motion base. However, for an enclosed capsule simulator at least, a 6-axis motion system can be represented very adequately by a 3-axis motion mechanism. Gravitational coupling to a pitch movement can produce pseudo-surge and the gravitational coupling to a roll motion can produce pseudo-sway. Because the body does not actually sense yaw itself, but yaw-rate (centrifugal force) instead, this can also be represented by adjusting the instantaneous pitch and roll vector to match the outward acceleration of the body undergoing yaw.

Such approximations are achieved at the expense of losing the "edges" of the surge and sway motions, since it takes a finite time to re-orientate the capsule in pitch or roll. Nevertheless, the simulation is usually quite acceptable. A 3-axis, heave, pitch and roll mechanism and an enclosed capsule is probably the most cost-effective option for many training purposes.

COMPACT SIMULATORS

It is important that the simulator motion base should not add greatly to the height of the simulation capsule. There are a number of designs of three-axis motion system in which the actuator rams are folded beneath the simulator in the form of a tetrahedron or of an inverted rectangular pyramid. These provide plus or minus 25 degrees of pitch or roll and 0.5 m heave from a folded or "loading" height of about 0.7m.

SEAT-ONLY MOTION SYSTEMS

Clearly, a simulator must have the lowest possible size and weight in order to reduce the power, cost and complexity of the motion system. With this in mind it has been proposed that the main body of a simulator might be fixed whilst the seat alone is moved; the idea being that only the driver feels the motion, so only the driver needs to be moved. But the idea of moving a seat separately to its fixed visible and tactile near environment breaks the most fundamental rule of motion simulation. It is vital that the real instantaneous position and orientation of the human being in a simulator shall not be perceptible to him/her. If the seat holding the occupant is moved – but he/she continually sees or touches something that is stationary - the illusion that the whole simulator is moving will be destroyed. It follows that the seat itself cannot be moved in relation to the controls.

The remaining option is that the seat occupant must be moved within the seat. After all, that is what happens in reality! The occupant of a moving vehicle is continually moved within the confines of the seat by the inertial effects of the vehicle motion. Providing that the corresponding visual and aural cues are provided and the occupant is focussed on the control task, the effect of the relative motion is that the seat feels as though it is moving instead.

This type of motion cueing system has many advantages, since the "g seat" mechanism can even be made a retrospective fit to existing stationary simulators. However, it should be recognised that seat motion cannot produce motion cues that are as powerful as those from motion platforms. That disadvantage is offset by the ability of the motion seat to provide long-period lateral acceleration cues and to provide wide bandwidth vibration, surface texture and turbulence cues.

A SIMULATOR WITHIN A SIMULATOR

When shock or vibration cues are an important part of the training for an air or surface craft, they must be present in the simulator environment. That is especially important for helicopter training. But it is impractical to apply such motion to the simulator as a whole, because the power required would be very large - and because it might actually damage the simulator. Motion seats within a motion base machine provide an excellent solution to this problem.

THE VISUAL DISPLAY INTERFACE

There is a strong interdependency between the choice of motion system and the choice of visual display system.

For example, for realistic driver training it is important that the driver believes that he/she has an all round view. This includes the wing and centre mirrors. One way to achieve this is to use a model of the vehicle cab surrounded by video screens to the front, side and rear. Ideally, the screens will be at a significant distance from the vehicle cab so that there is a strong differential focus between the control instruments on the dashboard, the extreme edges of the vehicle and the more distant view of the road ahead.

This can be achieved with six or more overhead projectors and a series of large screens surrounding the vehicle to front side and rear. Unfortunately, the complete simulator installation then has a significant size, weight and inertia, so that if the whole system is intended to be mounted on a motion base the mechanism has to be large, powerful - and very expensive.

There are other difficulties of construction in that the screens and the projector mounting have to be strongly constructed so as to resist the forces caused by the motion base. The foundations of the system must be substantial and the size of the room in which the moving object has to be located is that of a large hall. The Daimler-Benz simulator in Munich is a well known example of such a system.

COST REDUCTIONS

To reduce the size and cost of the motion system the weight and inertia of the structure may be decreased by using a series of TV screens in place of the vehicle windows. However the number of computing channels is increased because there are more TV screens than there would be projectors for a cinema screen system. To bring the number of computing channels to a realistic number it is possible to reduce to (say) five the number of forward TV channels, using (say) three other channels for the rear view system and eliminating the side view displays.

FIXED DISPLAYS - MOVING SIMULATOR

There is, however, a strong preference for the visual displays to be at a significant distance from the perceived edges of the vehicle. It must create the impression that most of the world in view is at a distance from the edge of the vehicle. If TV screens are used they have to use optical enhancements that put the image at infinity. Another form of simulator has therefore been devised in which the visual display screens and their projectors remain fixed and only the simulated vehicle is fitted to a motion base.

The problem with this idea is that the "virtual motion" effect is strongly dependent on the assumption that the simulator occupant does not know what his real motion actually is. In an enclosed capsule, for example, it is impossible to tell whether the capsule is pitched or rolled; so that when the appropriate motion cue is applied it is felt as a surge or sway acceleration. In the same way lateral acceleration such as heave is perceived to continue for longer than it actually does, because the "virtual view" shows the continuing action whilst the real movement is gently brought to a halt.

The illusion does not usually work well for a stationary display system. Although the simulator may be mounted in a darkened room there is always sufficient light reflected from the screen to show where the floor and ceiling are; so the occupant of the simulator knows which way is "up". There is also the problem that no significant pitch or roll motion can be used, because the trainee would then begin to see the edges of the screens. This instantly destroys the simulator illusion. Fixed screen simulator systems therefore use motion bases that only move through small angles - typically plus or minus five degrees in pitch and roll. That means in turn that the usual tricks of “surge acceleration cues from pitch motion” and “sway acceleration cues from roll motion” can’t really be used!

Douglas Trumbull, the special effects artist whose 1978 patent was one of the earliest on entertainment simulators, has taken this problem to its logical conclusion. Some of his wide screen simulators have no rotation whatever. Instead he uses the three lateral motions alone, as a stacked motion system, and makes all three motions very large. The resultant motion cues are extremely powerful!

Some thought and observation will also show that rapid motions of the simulator, produced by simulated road surface variations for example, should not be fed into the optical system. We are all used to feeling motion in a vehicle whilst we observe surroundings that we know to be fixed. Our head and eye stabilisation system and the workings of the brain compensate for the rapid variations of the vehicle position. Thus a visual display showing the rest of the world away from the vehicle *is not expected to move* and looks incorrect if it does so.

FIXED DISPLAYS - FIXED SIMULATOR - MOVING SEAT

It might be thought that moving a trainee in a motion seat would disturb his/her interface to the controls. However a study of body accelerations in a road vehicle will show that we expect to feel movements in relation to the seat - or seat motion in relation to us. When we turn left our body moves slightly to the right across the seat and visa-versa. When we brake we move slightly forward and when we accelerate we move slightly back. When we turn at speed our body rolls slightly on the seat surface and there is a continuous up and down motion that generally represents changes in our interface to the road surface. It is therefore possible to represent these motions by moving the person in a seat a small distance in the appropriate direction, corresponding to what would happen if the seat were fixed to the floor of a moving vehicle.

Another strong source of motion sensation in a vehicle is produced by the varying tensions of the muscles in the arms which link the body with the steering wheel and in the legs, which link the body to the foot control pedals. When braking, for instance, the limbs brace to prevent the torso being flung forward against the steering wheel, and when cornering at speed the limbs are used to keep the body upright against the centrifugal forces that tend to throw it left or right.

These forces may be represented in a simulator by tilting motions of the seat; pitching forwards to represent braking, pitching backwards to represent acceleration and rolling left or right to represent the centrifugal forces. These small tilting motions of the seat pan - in the same direction as the body would be thrown - can be applied at the same time as the small lateral motions of the seat in the opposite direction. In this way convincing motion cues can be generated from motion of a driver raining seat alone, the vehicle and the visual display screens remaining stationary throughout.

Although much of the foregoing relates directly to surface vehicles, it will be understood that similar considerations apply to aircraft training simulators.

VIRTUAL REALITY HEAD DISPLAYS

VR headsets provide an all-round view and can be designed to operate in an environment of vibration and even of moderate shock forces. Their chief disadvantage is that the optical systems presently available are cumbersome, so that the trainee becomes conscious of the artificial environment of the simulator. This is especially true in an environment of vigorous motion, in which the inertia of the headset can produce some very unnatural and disturbing forces on the trainee.

Clearly, it is possible to produce a small high-performance simulator by using a head display unit in combination with a simulator seat. The motion seat cueing device then has the extra advantage that the upper body of the trainee does not experience large inertial forces and there are none to the head.

SUMMARY

Recent improvements in the technology of motion bases allow them to be used indoors, to operate at lower power levels and to provide extremely accurate motion cues. Electromagnetic machines are silent and a group of small machines can operate in the same room without undue interference.

Motion bases provide the most realistic motion cues. They are essential for training when the driver or pilot is not seated, or when a team of persons acting together must learn to do so in a vigorously-moving environment.

The problem of latency in pneumatic “g seats” has now been overcome but pneumatic devices have now been superseded by electromagnetic actuators.

Motion simulator seats have been developed for more than twenty years and they have a number of useful advantages. However, it is incorrect to move both the seat and its occupant as a whole unit in relation to the surrounding environment. The occupant must actually be moved within the fixed seat.

Motion seats are the cueing system of choice when a wide bandwidth response is required – when it is necessary to simulate accurate changes in the vibration environment or when impulsive shocks are important to the training experience. Motion seats may be added to large motion base simulators as a means of increasing the bandwidth of the motion cueing system.

Motion seats have the additional advantage that they allow a wider choice of display system and permit significant reductions in simulator cost. They are ideal for portable or part-task trainers.

There is a very large entertainments market for motion seats, which is likely to lead to their wide availability at low cost. Motion seats are likely to make car-driving simulators more common – perhaps even compulsory.

