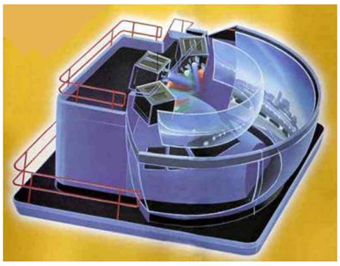
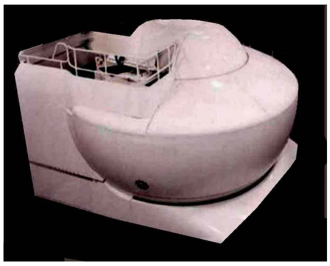
ANNEXES TO

MOTION AND VISUAL CUES
IN THE REAL WORLD
AND IN SIMULATORS



The two pictures on the left were produced by simulator Image Generators, not from photographs

by

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THE SIX DEGREES OF FREEDOM

These apply to any object that is free to move in all dimensions.

Such as an aircraft in flight, a submarine when underwater, a spacecraft, etc.

Type of Motion	Description of Motion	Scientific Symbol for Acceleration	Axis of Rotation or Motion	Name of movement
Angular Rates	Pitch Rate (nose up and down)	Ry	Lateral	Pitch
"	Roll Rate (wing up / down)	Rx	Longitudinal	Roll
"	Yaw Rate (nose left and right)	Rz	Normal (Vertical axis)	Yaw
Linear Movements	Vertical (whole body up and down)	Gz	Normal (Vertical axis)	Heave (Flight Simulator Terminology)
"	Lateral (whole body side to side)	Gy	Lateral	Sway (Flight Simulator Terminology)
"	Longitudinal (whole body fore and aft)	Gx	Longitudinal	Surge (Flight Simulator Terminology)

Part 1 - VISUAL CUES			
Serial	Real World Cue	Registration of cue by driver or pilot	
		Event	Timescale
1	**1. Outside Visual Scene** (Note 1)		
1.1	Displacement of horizon or objects in view	Displacement of visual scene, particularly the horizon. Particularly in aircraft at low level, takeoff, landing, etc	When displacement becomes noticeable (tenths of sec/secs)
1.2	Streaming of the scene through the visual field of the pilot or driver	Movement of visual scene inc objects & other scene detail	Continuous, if enough contrast features exist
1.3	Perspective changes in scene	Best with close vertical features	Continuous, if enough perspective features are present
1.4	High-G aircraft: Eye-Point lowering under G	Body slumps as G increases	Slow (seconds)
1.5	High-G aircraft: Loss of Vision under high G	As G increases, peripheral vision loss, then grey-out and black-out (G-LOC)	Slow, after 1.4 above
2. Inside Visual Scene (inside the vehicle cab or cockpit)			
2	Instruments, particularly flight instruments in aircraft	Changes of speed, heading. For aircraft, altitude, pitch & roll attitude, sideslip, turn rate, etc	When change is noticed (tenths of sec)

*Notes: 1. **Outside World, the Out of The Window (OTW) scene**. Peripheral vision is important in roll cues, the position of the horizon is important in pitch and roll cues, contrast and perspective features in the visual scene for all cues (particularly changes in perspective of objects at different distances from the Observer).*

*2. **Response - aircraft pilots**. Cues except those of visual streaming are first sensed by pilots as the aircraft moves after control inputs, or as a result of disturbances such as turbulence, asymmetric engine failures, etc.*

Part 2 - MOTION CUES

Serial	Real World Cue	Registration of cue by driver or pilot	
		Event	Timescale
1	Vestibular (Inner Ear) sensors (semicircular canals and otoliths, see note 1)	On acceleration being felt in the particular Degree of Freedom (DoF)	Rapid transmission of cue to the brain (tens of milliseconds)
2	General Forces on the Body, "Proprioceptive" cues from sensors in the muscles, joints, and viscera		
3	Small movements of torso and limbs, "Kinaesthetic" cues (see note 2)		
4	In aircraft, Skin Pressures, Tactile cues (Seat-of-the-pants, particularly for Normal G, pressures from the G-suit, straps, etc).		

Notes

*1. **Vestibular cues**. The Inner Ear (Vestibular Apparatus or Vestibule) is the human organ of balance and acceleration, and continuously sends signals to the brain. These cues are particularly important where outside-world visual cues are reduced, such as at night, in poor visibility, when imagery from Electro-Optical sensors is being used, etc.*

*2. **Kinaesthetic cues**. These are produced by small movements of the body, resulting in signals being sent to the brain. They are particularly important in registering accelerations in pitch, roll and "sway" (sideways motion), also linear acceleration & deceleration ("surge"). With roll motion, the upper body moves sideways, and with sway the whole body moves sideways. With pitch, linear acceleration and deceleration, the body moves forward or back. These movements trigger the subject's automatic muscle responses which aim to bring the body back to its original position and transmit these responses to the brain.*

*3. **Buffet and vibration**. Cues are also produced by short term, rapid small amplitude motions such as buffet, vibration etc. These may produce little or no effect on visual cues but the buffet and vibration cues are felt by the body's motion sensors.*

*4. **Aircraft response**. Motion cues occur after disturbances due to use of flight controls, turbulence, yaw after engine failure, etc., and follow the aircraft's short-period response (the Short-Period Oscillation, SPO), except for cues of high G, buffet and vibration. The aircraft response after a disturbance or flight control input cannot be faster than the rate of the SPO because the system cannot respond more rapidly.*

In the able below, the number of crosses is an approximate indication of the strength of the cue to the simulator subject (frequently an aircraft pilot), and is the author's subjective estimate for an average flight task. These show that the systems with most cueing capability are the Outside World (OTW) scene, the flight instruments, and a motion platform.

SERIAL	**CUE OF MOTION**	**SIMULATOR SYSTEM**				
		Visual (note 1)	**Flight Instruments**	**Motion Platform**	**G-seat (note 2)**	**Anti-G Suit**
1	Visual, good visibility by day	XXXXX	XXX			
2	Visual, poor visibility Visual, clear night Use of E-O sensors	X XX XXX	XXXX			
3	Instrument Flying		XXXXX			
4	Eye-point lowering under G				X	
5	Visual dimming under Hi G	XX				
6	Vestibular			XXXX		
7	Skin Pressures			X	XX	XXX
8	General forces on the body			XX		
9	Relative body movement			XX		
10	Buffet and vibration			XX	XX	
Interpretation of cues by pilot		Auto	Needs conscious effort & scan	Auto	Automatic	Auto
Weighting (number of crosses)		8 - 10	12	8 - 10	4	3
Need for min standard of training?		Yes	Yes	Notes 3/4	No, but highly desirable	

Notes:

1. **Outside World (OTW) Visual Scene**. Cues of the visual scene are strong when relative movement is taking place within the scene. Examples are horizon displacements or flow patterns of features of contrast through the scene. Cues are strongest in conditions of good visibility, with a clear view of a wide horizon, and where there are many points of contrast in the subject's view such as cultural features and texture. The visual cue becomes progressively reduced as these features diminish, such as in conditions of low visibility, low light, night, the use of Electro Optical sensors (NVGs, IR), and where a large horizon cannot be seen such as with a simulator display with limited view, or when the horizon cue is reduced or disappears.

2. **Motion-Seats**. The basic Motion-seat functions are:
   - Buttock pressure through a seat pad (seat-of-the-pants cue);
   - Eye-point lowering by lowering the seat-pan under high computed G;
   - Strap tightening under negative G and loosening under positive G.

3. **Cues of Real Motion from a Motion Platform**. These are needed if realistic motion sensation and fidelity of operation of flight controls ("handling fidelity") are a requirement.

4. **Simulator Sickness**. Strong visual cues over a wide FoV with rich scene detail, combined with no cues of real motion (or badly-synchronised motion), is a situation of "cue mismatch" compared to the real-world. Cue-conflicts compared to what the brain is used to processing, can cause symptoms varying from disorientation to nausea, after flight that can cause disorientation, being queasy, or even being sick.

FULL FLIGHT SIMULATORS (FFS) - U.S. FAA LEVELS *Regulatory Document: FAA AC 120-40B* *Blank box = not required*				
FAA FFS Level:	A	B	C	D
MOTION SYSTEM				
Minimum DoF	3	3	6	6
Special effects; ground rumble, buffet from thrust reverse & spoilers, bumps simulating gear travel		Yes	Yes	Yes
Buffet from mach effects, gear, flaps, stall, scuffing nosewheel				Yes
VISUAL SYSTEM				
Visual System minimum FoV (Horizontal x Vertical) at each pilot's seat	45 x 30 deg per pilot, simultaneous		Collimated, at least 150 deg horizontal	
Visual cues for Takeoff and Landing. Depth perception for takeoff (perspective & other cues) and sink rate for landing (texture for height judgement)		Yes	Yes	Yes
Quick Tests to confirm Visual System Performance			Yes	Yes
Dusk Scene to give horizon, fields, roads, lakes etc			Yes	Yes
Minimum of 10 levels of occulting (correct lines of sight with respect to terrain contours and 3-D objects)			Yes	Yes
Daylight Visual Scenes minimum 400 edges or 1000 surfaces (polygons), minimum brightness 6 foot-lamberts Night Scenes: minimum 4000 light points				Yes
MAXIMUM RESPONSE TIMES (Latencies)				
Max for motion, visual, & flight instrument response (milliseconds)	300	300	150	150
MODELLING AND OPERATIONAL REALISM				
Taxying & Ground Operations	Generic	All	All	All
Ground-effect for Takeoff and Landing		Yes	Yes	Yes
Reverse thrust aerodynamic and ground reaction model		Yes	Yes	Yes
Significant Sounds			Yes	Yes
Windshear Model			Yes	Yes
Realistic Landing deceleration, modelling runway, brakes & tyres			Yes	Yes
Quick test of programming & hardware (eg ATE)			Yes	Yes
Control Feel Dynamics to replicate aircraft			Yes	Yes
Realistic Sounds; cockpit noises, precipitation, wipers etc				Yes
Aerodynamic modelling inc Mach effects, aeroelasticity, icing, non-linearities in sideslip				Yes
Self-test performance tests, diagnostic analysis print-outs				Yes

TESTS ON A HAWK SIMULATOR

AIRCRAFT

This is the BAE Systems Hawk T-1 light fighter and advanced trainer, and the author had substantial experience on the aircraft. The US Navy T-45 Goshawk is a variant.

Flight controls. In the real aircraft, control forces are light and responses are rapid, particularly in roll.

SIMULATOR

The simulator was new and had a 6 axis motion platform, 3-channel visual, G-seat and G-suit cueing.

Taxying. Taxying was realistic with the motion platform ON and there were significant vestibular cues, undercarriage rumble and general vibration. Without the platform, taxying was bland and unrealistic, and required no skill to make steering corrections.

Takeoff. The motion platform gave a good cue of initial acceleration through what was felt as a "kick-in-the-back". This was followed by undercarriage rumble and realistic heading wander that required steering corrections. During acceleration on the runway, back pressure was achieved by the motion platform taking up a pitch angle so that pressure was felt, at the same time the instruments and outside scene maintaining level indications so that the subject's brain interpreted the back pressure due to platform movement as acceleration rather than pitch.

Climbs and Descents. Accelerations and Decelerations. Cueing was good with platform ON but poor without the platform. Without external visual cues (instrument flying conditions), accuracy was normal with motion but poor without motion with ***over-controlling in pitch***.

Pitch Changes - responses from the motion platform and the visual system made rapid pitch changes easy to make. Without motion the cueing was artificial ***and the intended G was frequently exceeded***.

Ground Attack Pull-Ups & Dives. Very good cue realism was found with the motion platform on. Without it, motions felt artificial, particularly in roll. Although manoeuvres could be achieved without the platform, ***tracking and height accuracy was poor***, but improved when platform cues were once more added.

Landing. On landing, the platform gave cues of undercarriage leg impact, undercarriage rumble, and good deceleration sensations with realistic heading wander, needing similar steering corrections to those required in the aircraft. The deceleration sensation was achieved by pitching the motion platform nose-down so that pressure was felt on the shoulder straps, at the same time maintaining level indications on the instruments so that the strap pressure was interpreted as deceleration rather than a pitch change.

> Motion off - Takeoff and Landing. Without motion, no steering corrections had to be made because there were no perceived disturbances due to crosswind, turbulence or general heading wander which occur in the real aircraft.

General. The most significant result was the poor accuracy of flying and untypical control strategy and/or scan pattern when the motion platform was not used. This was in Instrument Flying, formation (including simulated refuelling receiving), low flying, plus takeoff and landing.

More detail on accuracy is in the table that follows:

HAWK FLIGHT SIMULATOR TESTS - accuracies

Instrument Task	Accuracies		Remarks
	Motion ON	Motion OFF	
Straight and Level flight (S & L)	+/- 50 ft	+/- 400ft	With motion off***, control strategy and instrument scan were unusual compared to the real aircraft***. Also, in addition to poor pitch control, without motion there was a *continuous bank oscillation of about plus and minus 10 degrees*. This was difficult to suppress due to a combination of light control forces and little control "feel".
Levelling from climbs & descents	+/- 50-100 ft	+/-400-600ft	
Steep turns at 60 deg bank	+/- 50-100 ft	+/- 600ft	

Further remarks in the full Hawk report are worth repeating in full:

1. *Effects from the simulator G-seat or G-suit pressures were of little significance compared to cues from the motion platform*.

With motion off, the system verged on the unstable and the aircraft was difficult to control. A much *more rapid scan pattern than usual* had to be employed to avoid divergence either in bank or height.

In a simulator without motion, these effects would have to be suppressed, with control and stability characteristics diverging from those of the aircraft itself.

2. With motion on, not only were the accuracies better, control felt like the aircraft, and

where large corrections were needed, large control movements could be made without the danger of oscillation and over-control that was present without motion.

Without motion, this standard of simulation could not be used for meaningful training in instrument flying; it was a disconcerting and sweat-making experience, totally unlike the aircraft.

It should be noted that in a fixed-base simulator (without a motion platform), the control responses would have to be adjusted to suppress these effects and would not be "as aircraft", generally being made heavier, more damped and less responsive compared to the real aircraft.

3. On instrument approaches in cloud, normal control responses and accuracies were found with motion ON, and a controlled overshoot was made from 300 ft.

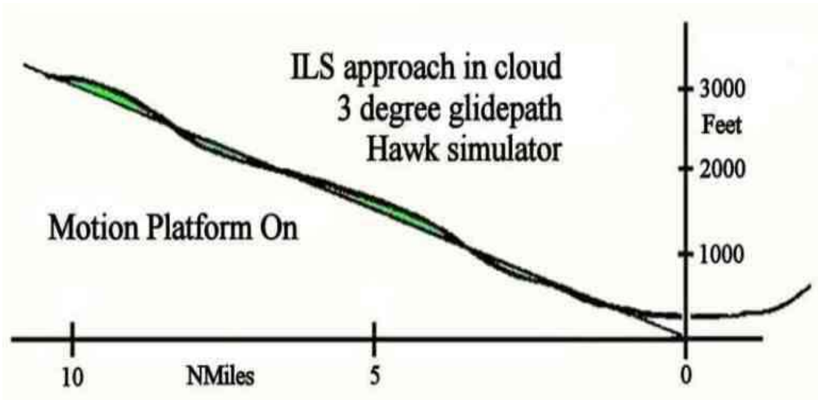
Without motion the approach was very inaccurate, particularly in glide path control. On an attempted overshoot, control was lost and the simulator "crashed" into the "ground" due to pitch over-controlling as the trim changes took place when the gear and flaps were travelling up.

This is shown in the instrumentation traces on the next page.

ILS INSTRUMENT APPROACHES – SIMULATOR FOR HAWK AIRCRAFT

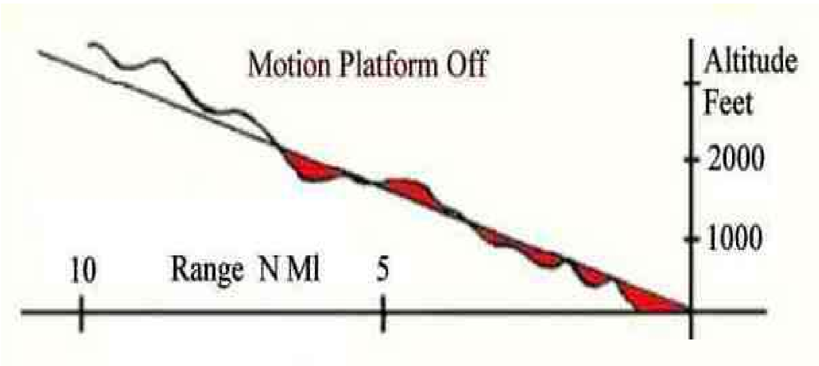
The first graph shows an Instrument Landing System (ILS) approach flown without external visual cues, simulating flight in cloud. An overshoot was carried out from about 300 ft, and slight oscillations in the altitude trace before climbing away are due to trim changes as the gear and flap retract.

The variations from the glide path are probably due to the natural Long Period Oscillation (LPO) of the aircraft which is not easy to suppress in cloud by control actions. The author had flown the Hawk aircraft and assessed the approach as very realistic compared to the aircraft itself and that meaningful Instrument Rating Tests could be carried out on such a simulator instead of the aircraft.



Immediately after the first ILS approach, the motion platform was disabled and a further instrument approach carried out with no external visual cues. This is shown in the diagram below.

Motion Platform Off. Despite the practice gained from the previous ILS, the second instrument approach was very difficult to fly, with constant and unrealistic control inputs being required to hold the glidepath. On attempting to overshoot from a range of about 1.5 miles from the threshold, the trim changes due to flap and gear retraction caused pitch instability. This could not be controlled by the pilot and the approach ended in a crash into the ground at a range of about 1 mile from the runway threshold. This can be seen in the above graph in the red shaded area on the extreme right.



Longitudinal characteristics.
In the lower graph, note the completely different and clearly unrealistic aircraft longitudinal characteristic compared to the upper graph, the handling for which was assessed as very like the aircraft itself.

Fixed-Base Simulators. In a simulator without motion, the instability and the unrealistic longitudinal characteristics shown in the lower graph would have to be compensated by altering the control and stability characteristics of the aircraft model.

In such a revised aircraft model, the aircraft would be less responsive and control forces would have to be increased, to avoid over-controlling, leading to major differences to the real aircraft.

Therefore, realism in use of controls and handling qualities generally, are reduced in a fixed-based simulator, compared to a Full Flight Simulator (FFS) with motion with well co-ordinated and realistic motion and visual cues.

ANNEX G

SIMULATOR TESTS

G1 This Annex starts with general comments on specific aspects of training as a result of simulator tests. More detail on the tests follows in Part 2 which starts on page 11.

G2 Instrument Flying (I.F.) - including Instrument Rating Tests (IRTs). When flying by sole reference to instruments, the horizon bar of the Artificial Horizon (AH) or the digital display equivalent, subtends a small angle to the pilot compared to the real horizon. The horizon bar pitch-gearing is typically one fifteenth of real-world pitch angles. There are also lags in the indications of pressure instruments such as airspeed, Mach, altitude and the Rate of Climb and Descent Indicator (RCDI). The I.F. control task using manual flight controls requies skill, particularly in turbulence, and Instrument Rating Tests (IRTs) are conducted regularly on all pilots. Full-scale vestibular and "body-movement" cues can only be produced in a simulator by a motion platform. These are needed if simulator-based IRTs are to be "as aircraft". An IRT on a fixed-base simulator would not be like the aircraft and would not test the pilot's capability, particularly in conditions of turbulence and wind shear. See the graphs in Annex F (page 8) that show the effect of lack of motion.

In a fixed-base simulator this can be compensated by changing aircraft characteristics, such as in the simulator altering the control and stability parameters to be more stable than the aircraft itself, and making the control forces heavier. Such a simulator would clearly not handle "as aircraft".

G3 Formation Flying – including Air Refuelling Receiving. With a well adjusted motion platform and a good aircraft flight model, these tasks can be accomplished realistically. Fine adjustments to control and stability parameters will almost always be needed during simulator acceptance testing. This particularly applies to "probe and drogue" fuel receiving where simulator responses to small pitch and roll (and occasionally yaw) inputs have to be positive and stable enough for the pilot to "fly" the probe into the drogue and keep it there while fuel is flowing. When the motion platform was switched off, accuracy of flying reduced, the task became difficult, close formation frequently could not be maintained and refuelling "contacts" become either erratic or impossible. This occurred in simulators for large aircraft and simulators of fighters with rapid responses to control inputs.

G3.1 Simulator adjustments to meet the Training Requirement - Formation flying and Air Refuelling. Adjustments often have to be made to a simulator so that the training requirement for critical tasks can be fulfilled. A particular case is air-to-air refuelling using either "probe and drogue" or "flying boom" systems. So that these adjustments do not affect other parts of the simulator flight envelope, they can be made to apply only within a certain distance from the tanker aircraft, typically about one kilometre. This volume is sometimes called the "refuelling box", and allows a set of control and stability parameters to be optimised solely for refuelling, for instance to enable the probe to be flown into the drogue in the simulator, and then held in position. What is generally found is that the control and stability of the initial simulator state is unsuitable for close-coupled precise control tasks like air refuelling. This leads to over-control and oscillation at the final stages of an approach to take fuel and later in what should be steady contact with the tanker while fuel is flowing. This is due to the difference in cueing between the simulator and the real-world and some differences in the derivatives and coefficients used in the simulator compared to those of the real aircraft. Whatever the reason, any over-control and oscillation in receiver refuelling must be damped down if the training task is to be achieved. Sometimes it is claimed that nothing should be done because "the simulator coefficients and derivatives are as-aircraft", but this does not allow for the differences of the simulator environment compared to that of the aircraft. ***In any case, it is imperative that the simulator must be adjusted if it is not achieving the training task***. Fortunately, it is straightforward to make adjustments to control responses and aerodynamic damping in a simulator so that the refuelling task can be achieved. If the "refuelling box" approach is followed, this will not affect other parts of the simulator envelope.

G4 Low Flying. Low flying in hilly terrain at speeds around 400 knots and target heights of about 250ft Above Ground Level (AGL) involves frequent lateral and longitudinal control inputs in order to contour-fly, to turn, and adjust for wind shear and turbulence, particularly in strong wind conditions. Motion cues of roll, pitch and longitudinal acceleration and deceleration are of particular importance so that the pilot can use the controls in the same way as in the aircraft, in combination with the visual cues that follow pitch, roll and acceleration in one or more of the 6 degrees-of-freedom (see Annex A).

If the training task is procedural rather than requiring control fidelity, such as route familiarisation or making an input to other entities in an overall simulation, then a much simpler training aid can be used such as a workstation with a simple visual screen, a control stick and a slider throttle.

G5 Stability and stick forces. Where an aircraft has low stick forces and/or low stability, without motion feedback there is a tendency in a simulator programmed with the real control characteristics for the pilot to produce oscillations in pitch and bank (particularly in bank). Since aerodynamic damping decreases with altitude, the effect worsens with altitude, and the tendency is exaggerated in simulated Instrument Flying because there are no external visual cues. These oscillations can be suppressed in two ways, either by altering the control and stability characteristics of the aircraft model so that oscillations can be damped, or by adding a motion platform to the simulation so that cues of real motion can be experienced.

G6 Manoeuvre in Degraded Visual Conditions. Motion platform cueing helps manoeuvring in conditions of degraded visual cues such as dull overcast, reduced visibility and/or low cloudbase, dawn/dusk and night, and flight by reference to sensors such as FLIR or intensifiers (NVGs).

G7 R&D and Control Law Development. Motion platform cueing is essential for the development or adjustment of aircraft control laws using a simulator. Unless properly-synchronised cues of real motion are present, as-aircraft handling will be impossible because the pilot's brain will expect cues to be similar to the real aircraft. Putting this another way, without cues of real initial acceleration on the pilot's body in the simulator, the pilot's reaction to disturbances will be slow and inaccurate compared to the real aircraft and simulator handling will not be as-aircraft.

G7.1 Prototype Gripen Fighter. After two accidents to prototype Gripen aircraft, a 6-DoF research simulator at NLR in the Netherlands was used by Saab for making adjustments to the fly-by-wire system for the flight controls. This simulator was used because a motion-based Gripen simulator was not available in Sweden. A USAF project on control fidelity also used the NLR 6-DoF system. See G9 and G10 later and the papers in the References.

G8 Helicopters. With good simulator motion feedback, activities such as hover, hover-taxy and slow speed flight are realistic and can be flown accurately. Without a platform, unless the control characteristics are altered from those of the aircraft, over-controlling develops (particularly on the collective lever), height-keeping and bank angles become inaccurate and landings are not properly under control, with erratic rates of descent and sideways motion. These are all classic symptoms of the lack of short-term motion feedback where pilots have to rely solely on visual cues that take longer to be processed by the brain than motion cues.

G8.1 Helicopter Development. The author flew a development simulator for a new attack helicopter in which the control and stability characteristics were set to be "as aircraft". This had a wide-view visual, the controls were light and responsive, and there was no motion platform. At the hover, the simulation was unstable near the ground and there was much over-controlling, particularly on the collective pitch control. The combination of wide visual, light controls and no motion is the classic way to induce over-controlling and oscillation, which then has to be suppressed by altering the control and stability characteristics of the simulator.

G8.2 First Fight of a Helicopter. A company chief test pilot carried out the first flight of a new type of helicopter, and said: "the aircraft felt like an old friend, and handled just like the simulator". The author flew this simulator later and confirmed this assessment. In contrast to the simulator in G8.1, this simulator had a 6-axis motion platform but only a 4 channel visual of not very good resolution, but with texture and a clear horizon cue. Realistic control responses were experienced and handling fidelity was assessed as good, although for operational training the visual system fidelity would need improvement.

G9 Space Shuttle. A unexpected longitudinal oscillation (PIO [1]) during the final approach to land occurred in an early flight of the US Space Shuttle. This was potentially dangerous to future Shuttle missions and was urgently investigated so that the PIO could be suppressed. However, the PIO could not be reproduced in the fixed-base Shuttle simulator that was used at the time. After further work in a simulator with 6-axis motion and existing Shuttle control characteristics, the oscillation was successfully reproduced. Changes were made to the control parameters in the simulator until the oscillation was suppressed. The result from the simulator was then used to adjust the control laws in the real Shuttle, and the oscillation did not re-occur in later shuttle flights. This shows the value of using motion-based simulation for problem-solving where unusual or critical flight control characteristics are concerned.

G10 B737 roll departures. In the 1990s, there were two fatal Boeing 737 accidents after departures in roll, due to rudder hard-over after a servo-valve failure (Colorado Springs 1991, Pittsburgh 1994). Recovery actions were developed using a test aircraft and a motion-based simulator. It was then found that the recovery procedures could not be practised successfully in a fixed-base simulator, but could be in a Level D Full Flight Simulator with motion.

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1 PIO = Pilot-Induced Oscillation

PART 2 - TESTS ON SIMULATORS

What follows is a selection of key points from reports on simulator tests made by the author and others. See also Annex F on Instrument Flight (I.F.) in a simulator for the BAE Hawk aircraft

Part 1. Fixed-Wing Civil Transport Aircraft
2. Large Military Aircraft
3. Helicopters
4. Fighter aircraft with centre-line thrust
5. Non-aviation simulators

Part 1 **FIXED WING CIVIL TRANSPORT AIRCRAFT**.

These simulators fulfil civil regulatory criteria (FAA, EASA and other Regulatory bodies) to either Levels C or D. All had 6-axis motion and visuals were Cross-Cockpit Collimated systems with distant focus and therefore showed similar images to both left- and right-seat pilots.

Boeing 737 (6-DoF Platform, Collimated Cross-Cockpit visual, 3 projectors)
This simulator had the Lateral Manoeuvring Motion (LM2) system developed by the Sabena Flight Academy and now marketed by Acceleration Worx of Louvain, Belgium (www.awx.aero/about-lm2). It was possible to switch off LM2 and return to original motion cueing so that the two systems could be compared. With LM2, it was noticeable that pure roll inputs resulted in pure roll cues, and cues during manoeuvres to keep on the runway approach centreline were assessed as realistic, contributing to a high handling qualities assessment when flown manually. With the original motion system, roll inputs produced both roll and sway cues.

However, in some types of aircraft both roll and sway cues may be produced in response to lateral stick if the cockpit is not close to the longitudinal axis of the aircraft being. A large airliner cockpit may be on the upper deck above the longitudinal axis, and this should be allowed for in its simulators by using roll motion backed up by a small amount of sway. In smaller aircraft, a pure roll cue will be appropriate.

Pitch cues for landings using LM2 and the original motion system were realistic and gave good handling training, with good pitch feedback from the motion platform during the round-out. **Without motion, landings were unrealistic and erratic, giving procedural training only with no sensory feedback.**

Boeing 747 (6-DoF Platform, Collimated Cross-Cockpit visual, 3 projectors)
Motion cueing was noticeable from the moment of push-back. Taxying was realistic with the platform giving yaw cues and small cues of wheel rotation that increased as taxy speed was increased. Pitch cues followed use of the brakes and thrust. **When the runway threshold was reached for takeoff, a high confidence had developed in the simulation**.
Takeoff. This was **impressively cued** with a strong cue of continuous longitudinal acceleration (kick-in-the-back) which continued into the climb-out. This was achieved by pitching up the cabin and pitching the visual at the same time so that the cue was perceived as pressure on the back and not as pitch.
Visual circuits. Motion cueing was impressive and felt particularly realistic in roll.
Landing. Touchdown was port gears first due to crosswind and turbulence. The platform cued each set of gear touching, and gave a realistic pitch-down on nose leg compression when wheelbrakes were used. Continuous deceleration was also well cued and gave a realistic feeling of leaning forward in the cockpit as speed reduced.
General. Bearing in mind that this simulator was still in acceptance testing and had not been finally tuned, **this was an impressive demonstration of cueing generally and motion platform performance in particular**.

Boeing 757 (6-DoF Platform, Collimated Cross-Cockpit visual, 3 projectors). The most effective motion cueing that I have experienced. **Very realistic in all flight modes and recommended for Instrument Rating Tests and Zero Flight Time (ZFT) conversions**. It shows the care and patience of the simulator manager (a retired airline pilot) who over a period of time has tuned this simulator for optimum cueing to match the aircraft.

Boeing 767 (6-DoF Platform, Collimated Cross-Cockpit visual, 3 projectors)
Motion platform cueing during this test was impressive, particularly in the cue of sustained longitudinal acceleration during and after takeoff, and vestibular cues of roll.
Instrument flight - felt like the aircraft and a full instrument rating on a simulator of this fidelity could be recommended. **The platform was then switched off and there was a step change in the standard of simulation and the device felt like a procedure trainer with a colourless, `flat' simulation; accuracy of flying decreased**. In this condition, training should be limited to procedures rather than handling, and Instrument Rating Tests (IRTs) should be on a motion-based simulator.

Concorde (6-DoF Platform, Collimated Cross-Cockpit visual, 3 projectors)

Although this was an old simulator, motion cueing was good with the platform on. The "kick in the back" on the reheat takeoff was realistic, as was body cueing in the steep after-takeoff attitude - these effects were achieved by pitching the motion platform up so that pressure was felt on the back and the extra platform pitch angle (compared to the actual aircraft pitch angle) would be sensed as acceleration. In terms of roll, the aircraft has a particularly lively roll response and this was well cued by the motion platform.

Without the platform - the simulation was flat and unrealistic, and **over-controlling in roll and pitch occurred when any but small stick movements were made**.

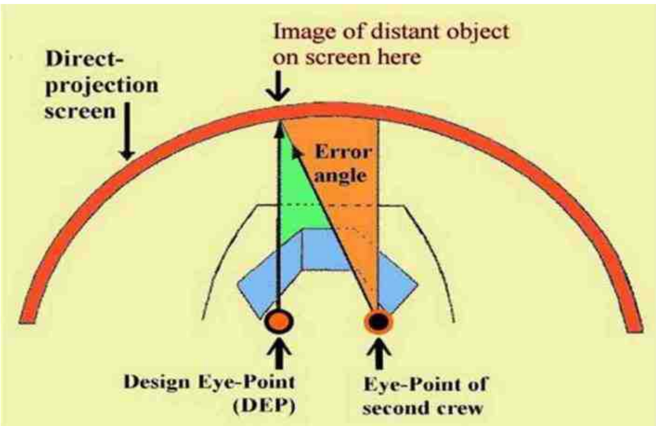
Saab 340 (6-DoF Platform, Collimated Cross-Cockpit visual, 3 projectors)

This was one of several new-build Full Flight Simulators in a UK training centre. The simulators were certificated to FAA and JAA/EASA standards and the Saab 430 was to Level C. Two approaches and landings were flown, one with motion and one without.

Without motion. The simulation was effective for procedural training but gave no sense of realism. When moderate lateral yoke was applied, there was a momentary sense of disorientation, probably due to the strong visual horizon cue not being backed up by the vestibular cue of roll that occurs in the aircraft itself. The pitch-up for landing was a guess and there was no "feel" during the round-out, landing roll, or taxying in.

With motion. **This felt like a real aircraft and light turbulence during the approach was very realistic**. Cueing in response to disturbance or pilot control activity was "as aircraft" as far as could be judged. **The pilot became immersed in the scenario as if it had been real flying**. The round-out for landing felt realistic and there was motion feedback that allowed precision in making the touchdown itself. The vibration and deceleration of the landing run was realistic and kept the pilot busy until the aircraft came to a stop.

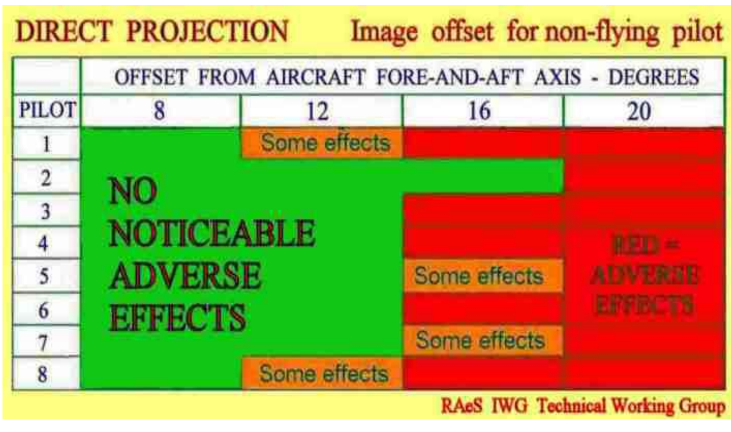
Simulator Image Offset with side-by-side Pilots and Direct Projection (non-Collimated) Display



With direct projection on to a screen, the geometry of imagery can only be correct from the "eye-point" for which the display system is optimised. Where pilots in a simulator are seated side-by-side, as in airliners, military transport aircraft and large helicopters, the optimised eye-point can be set for the pilot flying or a position between the two pilots. The diagram on the left shows optimisation for the pilot in the left seat, but there my be adverse effects for the other pilot, particularly where manoeuvres are carried out.

It is also possible to change the eye-point during a simulator sortie so that the pilot flying is always presented with the correct scene geometry.

Tests were carried out in a simulator where the display geometry was optimised for one pilot, and the display offset angle for the other pilot was deliberately varied between 8 and 20 degrees. The results from a sample of eight pilots are shown on the right. These indicate that offsets up to about 8 degrees have little noticeable adverse effects, offsets of 12 degrees led to adverse effects with some pilots, and only one pilot from the sample was unaffected by a 16 degree offset.



DIRECT PROJECTION — Image offset for non-flying pilot

PILOT	OFFSET FROM AIRCRAFT FORE-AND-AFT AXIS - DEGREES: 8	12	16	20
1		Some effects		
2	NO			
3	NOTICEABLE			
4	ADVERSE			RED =
5	EFFECTS		Some effects	ADVERSE
6				EFFECTS
7			Some effects	
8		Some effects		

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This also indicates that for side-by-side seating it is always better to use a Collimated (distant focus) curved mirror display system that enables both pilots to see essentially the same visual scene. For diagrams and more detail, see para 5.2.2 on page 6 of the main paper.

Part 2 - **LARGE MULTI-ENGINED MILITARY AIRCRAFT**

VC-10 (6-DoF Platform, 3 channel visual). Flew like the aircraft in most of the flight envelope, but there was a problem in air refuelling receiving using the probe and drogue system. It was difficult to get the probe into the drogue, and not possible to hold in contact to receive fuel. On turning the motion platform off, the situation became far worse with over-controlling and oscillation in pitch and roll.

After 6 weeks of development, the simulator was flown again. The control and stability characteristics in the refuelling receiver mode had been adjusted to reduce the tendency to over-control, simulator characteristics were much improved and **effective probe-and-drogue training could be carried out**.

Nimrod (6-DoF Platform, 3 channel visual). Very similar to the VC-10 report above. This simulator had to be adjusted to handle like the aircraft in probe-and-drogue fuel receiving. The manufacturer was able to do this by introducing a special handling model when near to the tanker (the "refuelling box") so that characteristics in the rest of the flight envelope would not be affected.

Nimrod – later simulator (6-DoF Platform, 3 channel visual). This had a later visual system with better texture than the earlier Nimrod simulator. The subject was an experienced Nimrod pilot. Manoeuvring at low level over the sea with 20 flap in turbulence was particularly impressive. A visual circuit was flown at a model of Gibraltar in adverse wind and turbulence, and was assessed as extremely realistic. The only criticism was that it was felt that, in simulating wind speeds and associated turbulence, the wind speed settings on the simulator should be re-calibrated so that the pilot would feel more effect. That is, the current 15 knot setting should be used for 10 knots, the current 20 knot setting used for 15 knots, and so forth. Particularly, the nil wind setting produced too bland an effect. The real air is hardly ever completely smooth and some slight disturbances were recommended as an automatic simulator setting even at low wind speeds.

The probe-and-drogue receiver mode had been worked on by the company and the Flight Simulator Liaison Officer (FSLO) was an ex-Boscombe Down test pilot with refuelling experience. The assessing pilot was able to make refuelling contact, push the hose onto the drum and stabilise in the refuelling position. A practice emergency break from refuelling was carried out and was realistic. Overall, this was the best air refuelling simulator handling that the assessing pilot had experienced, and illustrates the work put in by the company and the FSLO.

The motion platform was then disabled, and over-control and oscillations immediately occurred.

Simulator Image Offset with side-by-side Pilots and Direct Projection (non-Collimated) Display

See the diagrams and explanation on page 12. The situation applies to military aircraft in which two pilots are seated side-by-side, particularly where the separation is large. In these situations a Collimated (distant focus) curved mirror display system is preferred that enables both pilots to see essentially the same visual scene

Part 3 - **HELICOPTERS**

Apache AH-64 (6-DoF platform, dome visual)

Tests were made to qualify the aircraft for deck operations on naval ships varying from aircraft carriers to small frigates, in which turbulence, crosswind and deck movement are critical factors. A simulator with a 6-axis platform and dome visual was used because it was difficult, potentially hazardous and time-consuming to carry out the same tests using the aircraft itself on-board real ships, particularly when limiting conditions of aircraft control had to be assessed. For the simulator, handling and stability parameters for the Apache were modelled in a program specially developed to match the simulator characteristics, so that limiting test points did not have to be repeated in the aircraft on the various ships concerned. A safe flight envelope was developed and used in the aircraft release-to-service for shipboard operations. For some of the test points flown on the simulator, inadvertently the motion platform was not enabled and visual cues alone were available. **The test pilot assessed these visual-only/no motion conditions as extremely unrealistic, making no contribution to qualifying the aircraft for deck operations, and the test points had to be repeated with the motion platform on.**

Chinook and Merlin (each sim with 6-DoF Platform, 5 channel visual, seat vibrators).

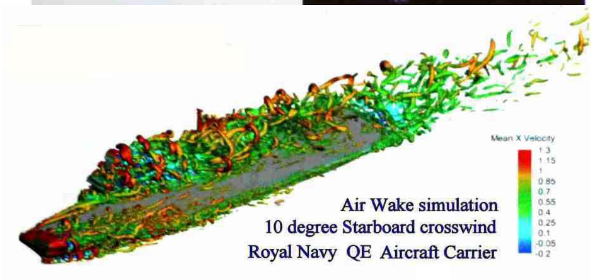
An experienced helicopter pilot and simulator instructor stated: "The overall balance of cues between motion, visual, sound and other cues is excellent. Motion in the simulator plays a vital part in low speed manoeuvre and landing. This particularly applies to training for sloping ground landings, confined area operations where there are obstructions, and in degraded visual conditions such as "brownout" or "whiteout". In these conditions, training using only the visual system with seat cues does not bring home the difficulty of controlling on a slope, nor the importance of controlling lateral drift in a brown-out or white-out touchdown. These remarks are based on about 10 years of simulator experience and I know are reflected by many experienced instructors."

<u>Helicopter tests flying from a UK Royal Navy Aircraft Carrier</u>

Airflow models were developed for the UK Queen Elizabeth class of Aircraft Carrier including a 10 knot crosswind situation. These were used in a Helicopter flight simulator with 6-axis electric motion and dome-based visual, as shown on the right.

A diagram of the airflow model is shown below with a crosswind from starboard. Approaches to the deck were flown from behind the Carrier and from positions on the port side.

When the simulator motion platform was used, handling was assessed as realistic. An approach was made **without motion but was assessed as so unrealistic** that the test pilot asked that he should not be asked to repeat it.



EH 101 Merlin (6-DoF Platform, 4 channel visual)
Hover-Taxying was possible with good texture cues and motion platform on, but was not possible with the motion platform off. Without the platform, when hover-taxying was attempted, high control activity was noted on the collective lever and fore-and-aft on the cyclic, and the pilot had to climb to avoid hitting the ground.
<u>Landing</u>. With the motion platform ON, touchdowns could be felt from individual undercarriage legs and the standard of simulation was very good, including heave (vertical motion) cues with Collective changes. Without the platform, the simulation was bland, had no realism or character, and felt artificial rather than resembling a real aircraft.
<u>Takeoff</u>. The simulation of takeoff was particularly impressive with the motion system ON, and the platform heave response to Collective gave particularly good cues. Without motion the simulation became bland and characterless.
<u>General Handling</u>. With the motion platform OFF and good visual cues, general handling was possible but the "feel" for what one was doing was lost and there was a step change in the quality of the simulation compared to Platform ON.
<u>Motion Platform</u>. The extra cueing and realism given by the motion platform was significant. **Some activities such as hover taxying and low flying with reduced visual cues were simply not possible without the platform** and a fixed-based simulator would have to have its control and stability characteristics changed from those of the aircraft.

<u>Generic helicopter type (Electric 6-DoF platform, 3 channel visual).</u>. This simulator had a small motion platform but nevertheless gave effective motion cueing, presumably due to low transport delay. When the platform was switched off, cueing was poor and unstable in the hover; hover-taxy was not possible due to over-controlling and the control laws would have to be damped if platform cues were not available.

<u>Huey (no platform, 3 channel visual)</u>. Control was difficult, particularly in the hover. Hover-taxy was not possible without gross over-controlling. It was stated that the control laws were "as aircraft", but **without the cues of real motion the simulation was difficult and unstable in some parts of the flight envelope**. If this simulator is to be used for practical training, the instability needs to be reduced, such as by altering the control laws from those of the real aircraft so that stable flight can be achieved. The alternative would be to add 6-axis motion cueing so that oscillations can be suppressed and handling made similar to the aircraft itself.

<u>Lynx (4-DoF Platform, 3 channel visual)</u>. Motion and vibration cues were very good, vibration cues being generated through the platform rather than through separate vibration devices. Yaw motion in stab failure drills was produced by the motion platform and was realistic, but without the platform there was no sense of motion and the drill was unrealistic. Without the motion platform, the simulation felt un-real and flying was inaccurate with occasional over-control particularly on the Collective when close to the ground.

<u>Sea Stallion (no platform, dome visual)</u>. Remarks as for Huey above. In addition, **an attack of "the leans" was experienced when flying round the circuit in good visual conditions but with no cues of real motion**.

<u>Sea King (6-DoF platform, wide angle Collimated visual, separate vibration devices under the pilots' seats)</u>
Cueing was good with platform on, but with the platform off, flying was inaccurate with general over-controlling near the ground in slow flight, in the hover and on landing. The vibration cues were good. It was reported that several pilots had felt `queasy' if the motion platform was switched off.

Comment on Simulation by the Chief Helicopter Pilot of a large company.
I am an ex-military pilot and instructor and have experience of both motion and non-motion simulators. By their nature, helicopters experience significantly greater forces in yaw and in the vertical axis than fixed wing aircraft. In my view, it is the fusion of adequate motion and visual systems which is the key to success in helicopter simulation. I have often seen (and experienced) quite severe motion sickness in non-motion helicopter simulators with high-quality visuals. **I have no doubt that motion is an essential prerequisite for a "top-end" simulation device**, though it may not be necessary for more procedural tasks.

First Flight of a Helicopter. A company chief test pilot carried out the first flight of a new type of helicopter, and said: "the aircraft felt like an old friend, and handled just like the simulator". The author flew this simulator later and confirmed this assessment. This simulator had a 6-axis motion platform and a 4 channel visual of not very good resolution, but with texture and a clear horizon cue. Realistic control responses were experienced and handling fidelity was assessed as good, although for operational training the visual system fidelity would need improvement.

Simulator Image Offset with side-by-side Pilots and Direct Projection (non-Collimated) Display
See the diagrams and explanation on page 12. The situation applies to helicopters in which two pilots are seated side-by-side, particularly where the separation is large. In these situations a Collimated (distant focus) curved mirror display system is preferred that enables both pilots to see essentially the same visual scene at all times.

Part 4 - FIXED WING FIGHTER AIRCRAFT WITH CENTRE-LINE THRUST

Hawk (light fighter/advanced trainer) (6-DoF platform, 3 Channel Visual)
See Annex F for accuracy table and instrumentation read-out for instrument approaches. The most significant result was the **poor accuracy of flying and untypical control strategy and scan pattern when the motion platform was not used**, particularly in Instrument Flying, formation (including simulations of refuelling receiving), and low flying. These defects were removed when the motion platform was used.

Hawk - 5-channel visual, G-seat, no Motion Platform
Manoeuvring was straightforward, seat buffet was realistic, but there were no vestibular and body motion cues.

Handling was not particularly like the aircraft and was an obvious simulation. The simulation felt "flat" and without "life", compared to fighter simulators with motion platforms. **The difference became more marked with increased rate of manoeuvre**. The impression of realism compared to real aircraft cues was low. 10 mins after the sortie, the pilot felt spatially disorientated and had to sit down for a while before recovering.

On a landing after a steep engine-failure approach (Practice Flame-Out / PFO), precise pitch control was difficult as the ground came up, landing was very heavy and would have broken an aircraft. This did not occur in steep PFO approaches in another Hawk simulator with a 6-axis motion platform where pitch control was assessed as similar to the aircraft. It appears that feedback from motion cues during the round-out is critical to realistic handling.

Lightning II simulator, F-35B version with hover capability

Simulator: 6-axis electric motion, wide angle visual, imagery with texture for objects, carrier deck, and sea states.

Exercises: Aircraft Carrier operation, Ski jump Take Off, approach and hover off port side, move sideways to centre of deck, high hover, descent to deck, avoiding hover near deck due to risk of hot gas re-ingestion. The picture shows an approach just before landing on the deck of the UK QE aircraft carrier.

Notes: RH control column and LH throttle are both complex with many switches and buttons, training essential.
Control forces - light on throttle, heavier on stick.

Handling: Without motion, the simulation felt bland and unrealistic with some over-control and oscillation, particularly in roll. Could be used for procedural training but not where handling is critical.
With 6-DoF motion, handled like a real aircraft, over-control and oscillation disappeared.

RN Test Pilot quote: "the most realistic environment and conditions I have experienced in a simulator".
RAF Test Pilot quote: "by far the most realistic simulator that I have ever been in, you sometimes forget that it is not real. You genuinely feel as though you are in the real environment".

F-16 simulators

The subject was a pilot with experience of a number of different types of F-16 simulators with visual systems from none to three windows, to one with wrap-around faceted visual. None felt like an aircraft, even those with high-resolution visuals. None were fitted with a simulator-specific G-seat or G-suit inflation. A combination of this and the lack of a motion platform made the simulations bland and flat compared to other fighter simulators that had motion cueing. Aerobatics and ground attack manoeuvres were flown in a simulator with wide-angle faceted visual, and although the view was impressive, there was no 'feel' of realistic flight.

Harrier (6-axis Platform, 3 channel visual, g-seat and g-suit cueing)

10 Conditions were flown with different combinations of visual, motion platform, g-seat and g-suit cueing, and a summary of the full report follows: The motion platform gave good cues of initial acceleration in all axes. Particularly good cues of sustained longitudinal acceleration and deceleration were noted, as were cues of yaw, sideslip (cued by lateral leaning), and heave response to nozzle changes. The short term responses to control movements were good and the vestibular (inner ear) sensations were assessed as similar to those in the aircraft, which the pilot had flown. No false cues were noted from platform operation, and instrument flying with the motion platform ON felt particularly realistic, as was control at the hover and vertical and rolling landings.

The visual horizon was also a strong cue, but with the motion platform OFF, cueing felt unrealistic and high pitch and roll rates produced slight feelings of disorientation that were not present with the platform ON.

Condition 3 (motion platform and all other cues ON) and, to a lesser extent, Conditions 5 and 10 (motion platform without g suit or g seat) felt like being in a real aircraft; all other conditions felt artificial and one was very conscious of being in a simulator.

When the motion platform was switched off there was a step change from "realism" to a "flat", character-less simulation with high artificiality, rather like going from stereo to mono when listening to music.

As well as improving cueing in the main flight envelope, platform cues included pitch and deceleration when using the wheel brakes on the runway, and to realistic sensation of acceleration on rolling take offs.

Overall. The motion platform made a vital contribution to operational effectiveness and **allowed hard manoeuvre, hover, and landings to be carried out effectively and precisely, which was not possible with motion OFF**.

Generic Fighter, no platform, head-slaved two-channel stereoscopic visual with unlimited FoV

Visual view was very impressive, a picture wherever you looked. However, the simulation did not feel like a real aircraft, more like a video game. **Shortly after the sortie, the subject felt nauseous for about 45 minutes but was not actually sick. Another pilot had to exit the simulator rapidly to prevent being sick.** It was later found that the two visual channels of the stereoscopic system were slightly mis-aligned.

Tornado (IDS version) (6-DoF Platform, 3 channel visual)

Without the platform - Instrument Flying felt "on a needle point", great concentration being needed to prevent divergence from target height, speed, and heading. **Instrument scan was artificially fast, over-concentrating on the artificial horizon and the altimeter and paying too little attention to other instruments**. Low flying without the platform included frequent inadvertent climbs to 600 ft radio height and there were constant bank oscillations through ±10º during normal flight. During approaches and landings there were inadvertent oscillations in bank and pitch through ±5-10º, and landings were heavy with over-controlling in both pitch and roll.

Platform on - **accuracies were improved and the cueing became significantly more realistic, often giving the impression that one was in a real aircraft**. This was particularly strong in Instrument Flying (I.F.), and when visual in conditions of longitudinal accel/deceleration and in rolling manoeuvres. It was considered that the I.F. simulation with platform on was sufficiently good to be counted as credits towards aircraft Instrument Rating Tests (IRTs).

Part 5 - **NON-AVIATION SIMULATORS**

Ship's Bridge Simulator.

This had a very wide view visual but no motion. It was a high-fidelity full-size replication of the ship's bridge with all of its windows. The visual display screens were outside the bridge windows showing realistic imagery including sea states. On leaving harbour and encountering sea swells with a long wavelength, there was a strong sensation of pitch and roll. Several people on the bridge (including me) held on to a solid object for support, even though there was no real movement. By looking back one could see outside the simulator and confirm that it was not really moving, but the sensation of movement was so strong that this check was made several times.

This motion was completely unlike that experienced in aircraft, having a much longer time period, so it is unlikely that lessons from cueing in Ship's Bridge Simulators can be read-across to aircraft simulators.

Exposure was about 20 minutes, and for about the same period afterwards a feeling of motion continued even though no motion was present. On leaving the simulator I had to concentrate on walking straight and there was a feeling that with less concentration I might stagger or even fall over.

The simulator owners stated that subjects had felt "seasick" in the simulator but no systematic investigation had been made. It is not known whether the "seasick" symptoms were because of the strong visual cues without synchronised real motion, or whether the subjects would have felt the symptoms on a real ship. This would be worth further research but would require a ship's bridge simulator with a motion platform such as those made by Kongsberg in Norway.

Ground vehicle simulators.

The subject had experienced several ground vehicle simulators for tanks, large trucks, and cars. Most had visual but no motion, some had 6-axis motion platforms varying from small electric to large hydraulic. Like aircraft simulators, those without motion were satisfactory as procedural trainers but gave little feeling of the vibrations and undulations of real road conditions. Those with motion gave very realistic cues of movement, but synchronisation with the visual picture of the ground was essential and in some cases not easy because of the close proximity of ground features to the subject.

Particularly realistic cues were experienced in a large truck simulator and a tank driver simulator, both of which had 6-DoF motion platforms.

Handling the 18 gears of the large truck simulator was a daunting task and showed the reason why simulator training for such a complex and expensive vehicle is cost-effective. The motion and sound simulation was particularly realistic, with pitch, acceleration and vibration cues accompanied by the usual squeaks and rumbles from engine and transmission systems.

On one type of tank simulator, manoeuvring close to trees led to collision with a tree being signalled despite the visual system showing good clearance - this was found to be because the "collision envelope" in the simulator program was considerably wider than the visual picture of the tree, and needed correction to co-incide with the visual imagery.

Annex H

SIMULATOR CUEING FOR `G' FORCES

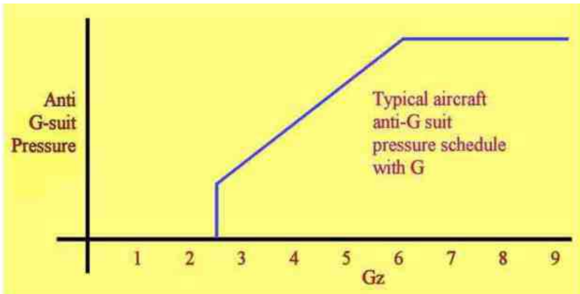
AIRCRAFT ANTI-G EQUIPMENT

H1. Aircraft high-G effects. As G increases, blood tends to pool in the lower legs, and blood pressure to the brain reduces. As blood pressure and oxygen to the brain fall, first there is loss of peripheral vision, producing a progressive "tunnel vision" effect. If high G continues, this is followed by loss of colour vision, sometimes called "grey-out". This is very dangerous because shortly afterwards, unless G is reduced, total loss of consciousness ("black-out") occurs. This is more properly known as G-induced Loss of Consciousness (G-LOC) and can be fatal if the ground is close. Because the brain has been starved of oxygen and takes time to recover, after consciousness is regained there is a period of mental confusion and spatial disorientation for between 10 and 20 seconds before normal judgement and skills are regained. Many aircraft fatalities have been attributed to G-LOC, and as many types of fighters are cleared to 9G in flight, some are fitted with systems to prevent it.

Pilot's inflateable Anti-G suit
This is the grey garment covering the abdomen and continuing to the ankles

H2 Anti-G Suits. An "anti-G suit" consists of special trousers with bladders that can be inflated to apply pressure to a pilot's abdomen and legs, to prevent blood draining to the lower body under G forces. A G-sensitive valve in the aircraft triggers inflation of the bladders, which press firmly on the legs, thighs and abdomen. The name is frequently shortened to "G-suit". Simulators for high-G aircraft should always include anti-G suit facilities, and anti-G suit pressures in the simulator provide a strong cue of high-G in the absence of real G forces.

H2.1 Anti-G Suit Pressure Schedule. in the aircraft, anti G-suit pressure is not applied at low G, but has a "cut in" or "onset" value at which the aircraft G-valve inflates the suit. As G is increased, the system increases the pressure in the G-suit progressively so that maximum pressure is exerted typically between 5 and 6 G and over. If partial pressure breathing at high G is employed, this facility can also be added to a simulator, see H5.



H3 Aircraft Cues of G. In the aircraft, the Anti G-suit onset pressure at between 2 and 2.5 G is a strong cue, being sensed by the pilot as a sudden push on the lower abdomen, combined with tactile pressure on the legs and thighs. At G values above G-suit onset, the primary cue in the aircraft is the G-force itself acting on the whole body, although in the range where G suit pressure changes with G (between about 2.5 and 6G), this produces an additional but minor cue compared to the real G forces.

H3 Eye-point lowering. As G is increased, the body is pulled down into the seat, it compresses and the eye-level lowers. The pilot senses the lowering of eye-point and, particularly where head-up instruments such as HUDs are being used, will use muscular effort to regain the original viewing angle in order to maintain the normal view over the aircraft's nose. This effect is easily reproduced in a simulator motion seat by deliberately lowering the seat pan under high computed G, causing the pilot to strain upwards to regain the normal eye-point, just like in the aircraft.

H4 Muscle tensioning**.** At high G, pilots are trained to adopt a muscle strategy (the "G straining manoeuvre") to tension the abdominal muscles. This, helped by the G-suit pressure, prevents blood from draining into the lower body. This can be trained in a centrifuge but not in a conventional flight simulator.

H5 Partial Pressure Breathing. Some aircraft such as Eurofighter Typhoon apply small amounts of partial pressure to the lungs under high G, through a well-sealed oxygen mask. This helps in maintaining blood pressure to the brain and the pilot's resistance to high G is increased. The author has tested this system in the air and it is effective in making high G easier to tolerate without strain. It is easy to apply in a simulator in response to high computed G where aircrew wear their aircraft equipment in the simulator.

CUEING FOR HIGH G - CENTRIFUGES AND DISORIENTATION TRAINERS

H6. Man-rated Centrifuges for high-G training have been made by Austria Metall System Technik (AMST) of Braunau, W of Linz, Austria; Environmental Tectonics (ETC) of Philadelphia, USA; Latacoere (Toulouse, France) and Wyle Laboratories (Los Angeles, USA). Currently, only AMST and ETC offer man-rated centrifuges for sale. The pcitures below are of an AMST centrifuge at the UK RAF base at Cranwell.

Modern centrifuge designs like the above include replica aircraft cockpits designed for sustained G, and their Outside World (OTW) visual systems encourage normal scan patterns. However, if a pilot's head is moved while under G in a centrifuge, feelings of disorientation (the "Coriolis illusion") can result because of the small rotation radius of the centrifuge compared to the much larger radius of a high-G turn in an aircraft. This can be partially compensated by strong outside-world visual cues but large head movements should be avoided in a centrifuge. Centrifuge training should be viewed as complementary to, not in competition with, the conventional flight simulator.

H6.1 Special G-LOC Training. G-induced Loss of Consciousness (G-LOC, see para H1 above) is particularly dangerous because when G is reduced and the pilot regains consciousness, there is a period of between 10 and 20 seconds of spatial disorientation during which the pilot is not able to accurately control the aircraft. During this period, the aircraft may fly into the ground. Therefore, training for pilots of high-G fighters should include centrifuge runs, perhaps at annual intervals. Fighter pilots often resist such training as uneccessary, but this is part of the extrovert, confident, fighter pilot ethos, and should not obscure the fact that many fatalities have occurred due to G-LOC. Clearly, if centrifuge training is available, it should be used. Such centrifuges must have realistic cockpit layouts and flight controls so that the pilot's body and limbs are in a realistic position, and task loading can be applied at the same time as the G loading. The pilot should also be able to wear normal flying kit in the simulator, which should be able to s**T**imulate kit such as the pilot's anti-G suit, aircraft systems such as presssure breathing under G, and so forth.

H6.2 Disorientation Trainers. Some "disorientation trainers" are designed to replicate the various spatial illusions that can be met in aircraft.

AMST Airfox Disorientation Trainer

They have full yaw freedom and can produce low-rate motion below the pilot's vestibular threshold.

Some are mounted on arms and act as small centrifuges capable of G values up to about 3. Companies such as AMST (Austria) and ETC (USA) currently produce disorientation trainers and centrifuges.

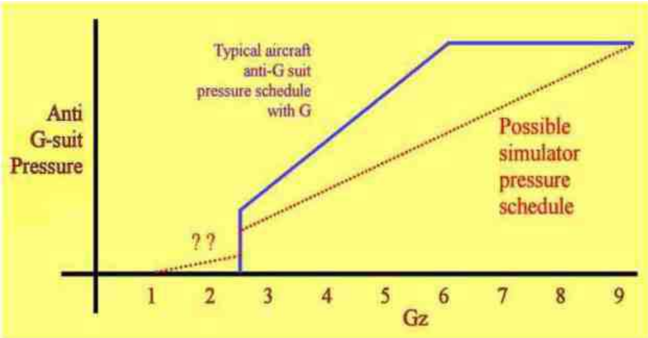
ETC GyroLab Disorientation Trainer

FLIGHT SIMULATORS

H7 **Simulator G-cueing devices**. These should include facilities for anti-G suits, G-seats, visual system G-dimming, and replication of pressure breathing where these systems are used in the real aircraft.

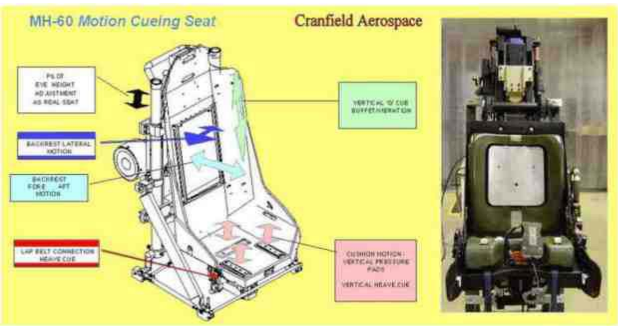
H7.1 **Anti-G Suits in Simulators**. A simulator can be fitted with an aircraft G-valve that inserts air into the pilot's anti-G suit. The valve is triggered by "Computed G" which is also used to feed the cockpit G-meter and other simulator systems such as a G-seat (if fitted). The simulator G-suit pressure schedule should be similar to that of the aircraft. The author has experienced a simulator G-suit system where inflation started at 1G and was linear thereafter without the sharp onset step between 2 and 2.5G; this was unrealistic and omitted a major cue which is easy to add to the simulator. In the aircraft, the onset step is a noticeable event, and should be reproduced. However the exact pressure of the step in the simulator is not particularly important. In fast-jet simulators that the author has flown, if the G suit pressure closely follows simulated G, then cueing for G changes is very good in the range where G-suit pressure has a high rate of change (typically 2.5-6G). Because of the lack of real G cues in the simulator, this should be exploited.

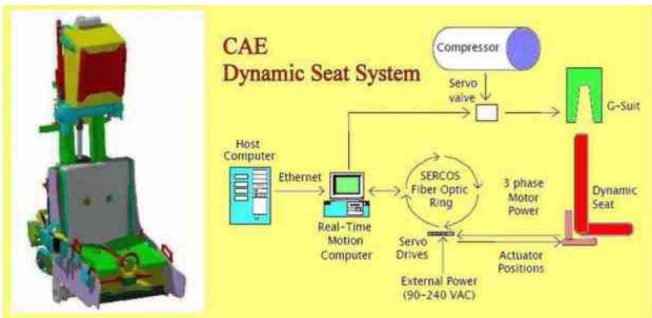
H7.1.1 **Anti-G Suit Drive Laws**. The G-Suit drive law should be under software control so that it can be adjusted for maximum effectiveness during simulator acceptance testing. It is also important that the simulator G suit pressure has a low lag with respect to computed G. In aircraft, this lag is of little importance but in simulators the author has flown with high G-suit pressure lags, the value of the cue is degraded. I have experienced a situation where G has been reversed in the simulator to negative and there is still positive pressure in the G-suit. This is a significant false cue and should be avoided. Research should be carried out on whether it may be beneficial to have a slight positive G-suit pressure at one G in the simulator, so that small changes to this can be used for G-cueing in the region between main G-suit pressure onset and down to the negative G regime.



SIMULATOR MOTION SEATS

H8. **<u>Motion Seats -General</u>**. Specially modified seats can be used in simulators to enhance various motion cues. For instance for increase in simulated G, buttock pressure through an inflateable pad in the seat, and seat-pan lowering. Also strap tightening under negative G, simulating being thrown against the straps, and strap loosening under positive G, simulating body slumping. Examples below are from Cranfield Aerospace (UK), and CAE (Canada).





H8.1 <u>Seat pressure pad</u>. This gives an effective cue of seat pressure under G, particularly for the lower G values before G-suit onset. I have also flown a simulator with multiple seat pads with different inputs, but these are complex, expensive, can give confusing cues, and are not recommended.

H8.2 <u>Seat-back pressure pad</u>. This gives an effective cue for longitudinal acceleration.

H8.3 <u>Seat pan lowering</u>. This gives the same effect as body compression under high G and is an effective simulator cue, particularly combined with pressures in the pilot's own anti-G suit at high simulated G. It causes the pilot in the simulator to stretch the body to raise the head as G increases, simular to what happens in the aircraft under high G.

H8.2 <u>Lags</u>. It is important that there is minimal lag in motion-seat cueing in response to computed G. The author experienced a motion seat with a large lag in operation, and when oscillatory stick movements in pitch were applied, the G-seat cueing became out-of-phase with the pitch motions of the simulator.

H8.3 Vibration devices. These can also be incorporated in the seat pan and can be effective in simulating stall buffet, also vibration in simulators for helicopters and ground vehicles.

H8.4 More Complex Motion-Seats. More complex motion-seats employ a variety of pressure pads on the seat pan and the subject's sides and back.

One device also had head-loading which placed downward pressure on a pilot's helmet at high values of computed G, this facility was later disabled due to possible adverse effect on the subject.

There are also types of motion seat which make movements like a small motion platform: such movements are too small to have much effect and such devices are not cost-effective.

Another G-seat had 26 different pressure pads over the seat and thighs; the author found this confusing.

Another type of motion seat had several different pads in the seat pan, and attempted to give roll cues by pressurising only one side of the seat pan at a time; the author found this confusing and unrealistic.

These complex devices are expensive, costing several times that of a basic motion seat with simple pressure pads in the seat pan and seat back, strap tightening, and seat lowering under G.

H8.5 **Motion-Seats in Fighter Simulators**. The author strongly supports the use of a motion seat for fighter aircraft simulators, but only with the basic seat cueing systems, not the more complex ones described in H8.4. Simple types of motion seats are available from companies including CAE (Canada), Cranfield (UK), Moog Amsterdam (Netherlands) and Sogitec (France).

H8.5.1 Cost of Motion Seats. The extra cost of a relatively simple type of motion seat is understood to be about US$30,000 over the basic cost of the dummy ejection seat in a fighter simulator. The more complex motion seats described in H8.4 can cost several hundreds of thousands of dollars and are not cost-effective.

H8.5.2 Motion seats with movements in one or more of the 6 Axes. Motion-seats that can move can produce only very small motion cues in all of the 6 axes, compared to the much lerge cues from a 6-jack motion platform. Such a motion-seat is only capable of small movements, vestibular cueing is minimal and such a device is not cost-effective.

VISUAL EFFECTS OF HIGH G - SIMULATOR VISUAL SYSTEM G-DIMMING

H9. Visual effects at High G. In the aircraft at high G loadings, the pooling of blood in the lower body and the reduction of blood pressure to the brain, leads to a number of visual effects. Due to differential pressure at the retina of the eye, one symptom is "tunnel vision" in which peripheral vision is lost but centre vision is retained. As G increases further, tunnel vision becomes narrower and colour vision is lost as the retinal rods take over from the cones that signal colour to the brain, a condition known as "grey-out". Unless G is relaxed, black-out (loss of conciousness) will soon occur.

H9.1 Simulator Image Generation. Visual symptoms of tunnel vision, grey-out, and black-out, can be simulated by a simulator Image Generation system in response to computed G, see the pictures below.

If a motion seat is fitted, as simulated G is increased, the seat pan can be lowered so that the pilot has to strech to maintain eye position, simulating body slumping under G in the real aircraft.

Annex I

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Listed in chronological order. Abbreviations include:

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DERA = Defence Evaluation & Research Agency, UK, now QinetiQ
NLR = National Aviation Research establishment, The Netherlands
RAeS = Royal Aeronautical Society, London

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