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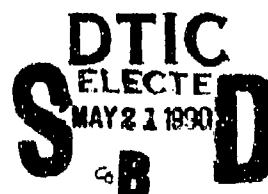
Technical Memorandum

October 1989

The Need For Platform Motion in Modern Piloted Flight Training Simulators

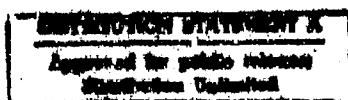
by

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Technical Memorandum FM 35

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THE NEED FOR PLATFORM MOTION IN MODERN PILOTED
FLIGHT TRAINING SIMULATORS

by

J. R. Hall

SUMMARY

This paper discusses motion cueing in piloted flight training simulators, and presents the factors that must be taken into account when assessing the need for, and benefits of, a motion platform so that informed decisions can be taken as to its training value. These factors include the role of the simulator, the handling qualities of the vehicle concerned, the tasks the pilot is required to fly, the performance he is expected to achieve and whether training considerations require him to use a similar control strategy and control activity in the simulator as in the aircraft.

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1 INTRODUCTION

There remains considerable debate on the need for, and benefits of, platform motion in modern piloted flight training simulators, especially where good outside world visual cues are provided. That this debate continues is due largely to a lack of understanding of the effects of motion cueing in piloted flight simulators, and the use in the past of motion platforms whose performance was not adequate to generate the motion cues they were designed to provide. This paper sets out to explain the purpose of motion cueing and to present the factors that should be taken into account when assessing the need for, and benefits of, a motion platform so that informed decisions can be taken as to its training value. These factors include the role of the simulator, the task the pilot is required to fly, the handling qualities of the vehicle concerned and whether training considerations require the pilot to adopt a similar control strategy and control activity in the simulator as in the aircraft. Thus the need for motion is driven more by the training role of the simulator than by the type of aircraft it represents (fighter, heavy or rotary wing).

Section 2 describes how the human body senses and perceives motion, and indicates in what circumstances one might expect motion cues to improve the pilot's task performance and make it and his control activity more like that seen in the real aircraft. Section 3 categorises the various sources of aircraft motion. Section 4 describes the motion cues that can be generated by current production motion platforms and concludes that these are generally consistent and compatible with the motion cues that sections 2 and 3 indicate are required. Section 5 cites some of the experimental evidence which identifies the flying tasks and aircraft handling qualities for which motion cueing is required if the pilot is to achieve in the simulator a level of performance and control activity similar to that in the real aircraft. Section 6 summarises the experimental evidence and discusses some of the wider issues pertinent to training simulators. Finally, the conclusions and recommendations of the paper are given in sections 7 and 8 respectively.

2 HUMAN PERCEPTION OF MOTION

Motion is sensed and perceived by pilots in four ways:

(i) Vestibular organs

These comprise the semi-circular canals and otolith organs in the inner ear. These sensory organs are analogous to a strapped down inertial navigation system and, over the higher frequencies of interest here, transduce (ie enable the pilot to perceive) the angular velocity and linear acceleration of the head respectively. They also give rate of change of angular velocity and linear acceleration. In normal earth-bound life it is these organs that endow us with the sense of balance.

(ii) Touch (tactile and somatic) sensors

These sensors are stimulated by the pressure or force applied to any part of the body and signal the linear acceleration and rate of change of acceleration to which the body is subjected.

(iii) Kinaesthetic sensors

These transduce limb, body and head orientation and the muscle forces required to hold a given position. The kinaesthetic sensors thus again provide information on the forces applied to, and hence the acceleration of, the pilot's body.

(iv) Visual

The eyes detect motion essentially as a change in position (or, to a lesser extent, velocity in peripheral vision), and detect velocity and acceleration by assessing changes in position over a period of time. The eyes have no ability to detect acceleration directly.

The vestibular, touch and kinaesthetic receptors are known as the proprioceptive sensors and measure the applied forces, linear accelerations and angular velocities (and their derivatives) acting on the pilot, and hence on the vehicle. Together they give rise to the 'seat of the pants' sensations by which some pilots claim to fly. When applied for a finite time, these forces and angular velocities (and their derivatives) will result in a change in velocity or orientation of the vehicle which can then be sensed visually.

The proprioceptive (vestibular, touch and kinaesthetic) receptors can thus give the pilot advanced warning about future changes in the motion of his vehicle which is not available to him from any of his other senses, and thereby enable him to react to the motion of the aircraft earlier and quicker than would be the case in the absence of these cues. The proprioceptive sensors become increasingly effective in this regard as the rate of change of aircraft motion increases. Furthermore, whilst proprioceptive cues require no attention from the pilot and are difficult to suppress, visual cues require both attention and location by the pilot and are easily suppressed (Staples 1970).

The proprioceptive sensors are unable to distinguish between a true linear acceleration and a slow change in the direction of the gravity vector as a result of the body and head being tilted. This feature is exploited when driving motion platforms.

Of the remaining human senses (sound, taste and smell) none are considered to contribute to a pilot's appreciation of aircraft motion in the short term and only sound may contribute in the long term.

3 SOURCES OF AIRCRAFT MOTION

It is useful to distinguish between two types of motion (Gundry 1976) when considering the effects of platform motion on the pilot's ability to control his vehicle and achieve a task performance and control activity representative of the real aircraft:

- (i) Disturbance motion is defined as a change in aircraft motion due to disturbances arising from outside the pilot's control loop which cannot be predicted by the pilot. Disturbance motion can be further subdivided into:
 - (a) Disturbance motion resulting from a continuous but random external disturbance such as turbulence.
 - (b) Disturbance motion arising from a sudden external disturbance such as a large gust, windshear, ground effect or some failure of any component of the airframe, engines or systems.

- (ii) Manoeuvre motion is defined as a change in aircraft motion arising from within the pilot's control loop as a result of pilot control action.

Manoeuvre motion can be further subdivided into:

- (a) Manoeuvre motion arising from the pilot initiating a change in the flight path or flight condition of his vehicle (eg most speed changes and all air-to-air combat manoeuvring with the exception of the final precision tracking task when using bore-sighted missiles or guns).

When a pilot makes a control input, and is content to wait a finite time before making a further control input, then he is said to be operating at low gain and exercising low gain, largely open loop control over his vehicle.

- (b) Manoeuvre motion arising from the continuous control inputs required to accurately track a moving object (including target tracking, formation flying and air-to-air refuelling) or to follow a continuously varying flight path (including low level terrain following and helicopter Nap-Of-the-Earth (NOE) flight).

When making continuous high frequency control inputs in order to achieve a given task the pilot is said to be operating at high gain and exercising high gain, closed loop control over his vehicle.

- (c) Manoeuvre motion arising from the continuous control inputs required to control a vehicle which has low dynamic stability (eg some failure or reversionary modes, unaugmented VSTOL aircraft and helicopters in the hover, etc).

This is invariably a high gain, closed loop control task.

In general, the pilot's control strategy and control activity varies continuously between high gain closed loop, and low gain open loop, control depending on the parameter being controlled, the characteristics of the vehicle and the nature and difficulty of the task.

Disturbance motion is frequently followed immediately by manoeuvre motion, as the pilot regains the required flight path, and under certain circumstances aircraft motion can vary continuously between disturbance and manoeuvre motion.

Random or regular motion cueing which does not disturb the motion of the vehicle sufficiently to require pilot intervention and correction in the short term, ie random or regular vibration including buffet and helicopter rotor effects, is not addressed in this paper. It is recognised that high vibration levels can seriously degrade a pilot's ability to perform a given task, in both the short and long term, and that certain vibrations and jolts can be used to fly the aircraft near a performance boundary (eg buffet), to cue the pilot as to discrete events (touch-down, stores release, weapon firings, etc) or to detect abnormal conditions or impending malfunctions (eg engine vibration). These motion cues are generally high frequency and low amplitude, do not have direction and do not require a motion platform for their simulation. They must, of course, be provided in a simulator whenever they are used by the pilot, or affect the pilot's ability, to fly a given task in a given vehicle.

4 PLATFORM MOTION SYSTEMS

The arguments presented in this paper assume a synergistic or stacked motion platform which has a high performance and which is integrated with the total simulator to provide cues at the same time relative to all other cues as they would occur in flight. Centrifuges and other specialised devices are not addressed.

The limited travel of platform motion systems clearly prevents the generation of the full motion cues of the aircraft as they occur in real life (except for some very specific flight regimes such as the steady precision hover of a Harrier or helicopter). Unlike most other simulator cueing systems, therefore, the motion platform does not aim to reproduce real-life cues but to 'stimulate' the pilot so that he 'perceives' the motion cues that he requires in order to fly the simulator with the same performance and control activity as he would the real aircraft (Tomlinson 1985).

To constrain the motion platform within its physical excursion limits, the signals defining the motion of the aircraft are passed through high pass filters before being used to drive the platform. These filters remove the longer lasting, ie lower frequency, components of aircraft motion and allow the motion system to be returned to its datum position at accelerations and velocities which are below the pilot's threshold of perception. These filters are of little significance in the three rotations where an aircraft's inherent roll damping, maximum allowable normal 'g' and maximum directional control power naturally limit the duration of any rotational accelerations that can be generated. Furthermore, the longer term longitudinal and lateral aircraft acceleration cues can be simulated to a limited extent by tilting the cockpit

to make use of the gravity vector. It is in the simulation of aircraft normal acceleration or 'g' that platform motion is principally deficient. It clearly cannot simulate sustained normal 'g', such as occurs when performing a tight turn or pull-up. Whilst it can simulate the short term changes in 'g' typical of manoeuvres of fixed wing aircraft, such as occurs when changing the radius of a turn or pull-up, it is not practical within the travel available on current production motion platforms to simulate the longer lasting changes in normal 'g' which a pilot requires to accurately control height in the hover in a helicopter or VSTOL aircraft.

Other systems, such as g-suits and g-seats, can augment platform motion. G-suits are an aid to the cueing of sustained normal 'g'. G-seats were also originally conceived as a means of improving the pilot's perception of sustained normal 'g'. Recent work (White 1989), however, has shown that the, predominantly somatic, motion onset cues generated by modern, high bandwidth, g-seats are sufficient to enable a pilot to hover a helicopter simulator with a similar performance and using a similar control activity to that which he uses in real life. Experience to date, however, suggests that g-seats are more effective in cueing for manoeuvre motion, where motion direction is less important, than for disturbance motion where the direction of the motion is of the essence. This is because the cues provided by a g-seat are an inevitable compromise and the cueing of motion direction, in particular, is to some extent unnatural and has to be learnt. For example, an increase in the load on the pilot's ischial tuberosities (ie seat of the pants) must be accompanied in the simulator by a decrease in pressure or skin contact area elsewhere. This can result in contradictory cues. Pilot criticisms of g-seats, including suggestions they move in the wrong direction under certain flight conditions, are thus not uncommon or unexpected, especially when the g-seat is being used to cue for disturbance motion. Platform motion thus remains the only currently available technology that provides motion cueing of both direction and magnitude that does not require to be learnt. This is because it stimulates the pilot's proprioceptive sensors in the short term in the same manner in which they are stimulated in flight.

Platform motion can thus be used to give a pilot direct information, via his proprioceptive sensors, on both the direction and magnitude of the more rapidly changing moments and forces acting on his vehicle before it has had time to react to the new applied forces and to move. This gives the pilot advance warning of a vehicle's subsequent motion, which is not available from any of his other senses, and allows the pilot to react more quickly to the

motion of the aircraft than would be the case in the absence of platform motion. He can thus correct for any deviation far earlier, and thereby reduce the magnitude of the deviation, than if he has to wait to obtain the same information visually.

A useful analogy is a well behaved servo system (the aircraft) which is required to track a given object. Where this object is slowly moving and predictable then only a low gain position feedback loop (via the pilot's eyes) is required to achieve a good tracking performance. As the object's movement becomes more demanding and unpredictable, then the gain of the position feedback loop (via the pilot's eyes) must be progressively increased to retain the same tracking performance, and the stability of the control loop reduces. The stability of the control loop can only be restored by introducing lead, eg acceleration feedback (via the pilot's proprioceptive sensors and platform motion cueing).

5 EXPERIMENTAL EVIDENCE

5.1 Disturbance motion

(i) Flight in turbulence

Experimental results (Gundry 1976) of flight in turbulence when performing a precision tracking task (eg an approach to land) show a reduction in aircraft excursion and an increase in the occurrence of high frequency, low amplitude pilot control movements in the presence of motion. In particular, the presence of motion causes an alteration in the pilot's output consistent with more rapid and more accurate control of his vehicle, and pilot performance and control activity is closer to that seen in real life. In contrast, for flight in turbulence which does not involve a precision tracking task, nor any other rapid corrections by the pilot, motion does little more than add a greater sense of subjective realism.

(ii) Windshear or system failures

The experimental evidence (eg Gundry 1976, Perry & Naish 1964) shows that motion allows a pilot to react far more quickly to a sudden disturbance due, for example, to a windshear or some failure of the aircraft or its systems (eg an asymmetric engine failure). Further, motion is found to be a significantly more effective cue in this regard than a wide Field-Of-View (FOV) outside world visual display system. The need for motion varies from essential, where the pilot must identify and correct for the disturbance in the shortest possible time in order to prevent an

unacceptable excursion from the desired flight path or in a critical flight parameter (eg sideslip), to unnecessary where the failure is comparatively benign and only requires a long term adjustment to the trim of the aircraft.

In summary, disturbance motion allows a pilot to react correctly and far more quickly to a disturbance because it provides a more rapid and relevant alerting cue than can be obtained visually. Disturbance motion requires motion cueing of both direction and magnitude if the pilot is to take early and effective corrective action. Direction, promptness and correct correlation with all other cues are, however, more important than the magnitude of the cue (Caro 1979).

5.2 Manoeuvre motion

Manoeuvre motion gives the pilot additional sensory feedback about the consequences of his control actions, the appropriateness of his control movements and the handling characteristics of his vehicle (Gundry 1976). Because it provides information earlier than visual cues it allows the pilot to correct more rapidly for an inappropriate control movement. It is useful to consider manoeuvre motion under three headings:

(i) Open loop control

For normal manoeuvring the pilot is operating to a large extent open loop and there is a lack of definitive evidence that motion improves pilot performance under these circumstances (Gundry 1976). Whether or not this is because of the low levels of motion cueing available at these control frequencies with production motion platforms is not known.

(ii) Closed loop control

As the manoeuvre task requirement becomes more demanding, and pilot gain increases, motion cues become increasingly important. For good control of helicopters in aggressive NOE flight, Buckingham (1985) has shown that motion cueing is marginally more important than a wide FOV display of the outside world and that the absence of both leads to a dramatic reduction in pilot performance and in the perceived handling qualities of the vehicle.

(iii) Control of a vehicle having low dynamic stability

There is overwhelming experimental evidence that motion cues become increasingly important as the dynamics of the vehicle approach an unstable region (Gundry 1976, Hall 1978). Hall (1978) has shown that motion is more important than wide FOV for controlling a Harrier in roll in jet-borne flight at slow speed, and that the absence of both leads to a dramatic reduction in pilot performance and the perceived handling qualities of the vehicle. Learning to hover a VTOL aircraft simulator in the absence of motion cueing has been compared with riding a unicycle without being able to feel the onset of an imbalance condition (Caro 1979).

Research reviewed by Gundry (1976) suggested that manoeuvre motion was only required when the dynamics of the vehicle approached an unstable region. He argued that this was because it is with unstable vehicles that control at high frequencies becomes most important, and it is the higher frequency control regime which benefits from motion cues. The work of Buckingham (1985) and other anecdotal evidence when flying high gain tasks, including precise tracking and air-to-air refuelling, suggest that control at high frequencies can also become important for stable vehicles and that these tasks also require motion cueing. This is to be expected because the stability of the total pilot/aircraft control loop will be reduced as the pilot's gain increases.

6 DISCUSSION

In summary, there is a large body of evidence (Gundry 1976) which shows that cockpit motion alters pilot control activity and task performance in a describable and reproducible manner. Motion allows the pilot to achieve a task performance and control activity which is closer to that seen in real life because he is using a similar set of sensory cues and piloting skills to those he would use in flight. This is increasingly true where the pilot is required or forced to operate in a high gain manner. This may be due to task requirements, the need to act promptly and correctly to an external disturbance or to control a vehicle having low dynamic stability.

The need for a motion platform thus depends largely on whether the pilot has to react quickly to a rapid change in aircraft motion in order to achieve a required task performance, pilot workload or control activity. This can be established by an analysis of the tasks the pilot is required to fly in the simulator, the handling characteristics of the vehicle concerned, the

performance he is expected to achieve, and whether training considerations require him to use a similar control activity in the simulator as in the aircraft.

Unfortunately, there is a lack of definitive evidence that correct pilot performance and control activity, and hence motion, are synonymous with the optimum transfer of training, or even that motion aids training (Gundry 1976, Caro 1979). However, it is not unreasonable to expect that a similar pilot performance and control activity in the simulator as in flight will contribute to good transfer of training of aircraft piloting and handling skills. At the very least it will improve pilot acceptance of the device as a training aid. Further, in a modern aircraft where flying the vehicle is becoming an increasingly smaller element of the pilot's total task, a disproportionate increase in pilot workload in flying the simulated vehicle will have an adverse effect when training a pilot to operate the total weapon system. To be an effective training device, a similar pilot workload will be required in the simulator as in flight, and this in turn will require either platform motion cueing or 'adjustments' to the simulation to modify the dynamic behaviour of the aircraft mathematical model to compensate for the absence of motion cueing.

Motion is of comparatively little importance when the vehicle is easy to fly, the task is easy to achieve with a low pilot workload and gain, and disturbance motion is either absent or does not require prompt corrective action by the pilot. Where this is the case, others have argued that platform motion is unnecessary since the simulator can be made to feel subjectively the same as the aircraft by increasing the perceived stability of the vehicle. The use of a dynamically incorrect mathematical aircraft model in order to compensate for the lack of motion cueing is only acceptable where the principal training task is essentially tactical or procedural: eg for air to air combat simulators, procedural trainers and weapon system trainers, including radar and air-intercept trainers. It is not acceptable when either an appreciation of the handling qualities of the vehicle or tasks involving high pilot gain, closed loop control are any part of the training role of the device.

It is commonly argued that pilots are taught to ignore motion cues when flying on instruments, and hence motion cueing is not required for instrument flying training in simulators. This argument fails to recognise that pilots are sensitive to both long and short term motion cues, and whilst they can and do learn to ignore the longer term motion cues, which are responsible for the condition known as the 'leans', they still sub-consciously perceive and use short term motion cues for controlling the vehicle.

It should be noted that, because motion is perceived sub-consciously, a pilot may be unaware that motion is responsible for his change in performance. The author found that when he progressively removed the roll motion cueing from pilots flying a vehicle having low dynamic stability (a Harrier at low speed in partially jet-borne flight - Hall 1978) they frequently blamed a system failure for their dramatic deterioration in performance and were unaware that they had lost roll motion cueing.

Motion is a very powerful cue which requires no attention from the pilot and is difficult to ignore in the short term. The platform must therefore stimulate the pilot in such a way that he perceives the motion to be representative of the real aircraft. Furthermore, advance information about the future motion of the aircraft by way of motion cues is of little consequence if the phasing of the motion cues relative to all other cues, eg due to delays in the motion platform, result in them being presented to the pilot after the visual cueing systems have moved. Stimulating aircrew in a manner that conflicts with learned experience of the real world will adversely affect their performance and acceptance of the simulator. In some cases it may lead to disorientation and sometimes even a feeling of nausea. Of greater concern is that a pilot will adapt to conflicting cues, if exposed long or often enough, which could lead to negative transfer of training or even disorientation on return to the real world.

The evidence to date for using platform motion cueing in training simulators has been obtained largely using low performance motion platforms, and it is strongly suspected that past experiments which have failed to demonstrate the benefits of motion, or motion platform systems which have been found to be unacceptable and have been turned off, have either provided false cues or suffered from excessive lags. Modern motion platforms are more capable and may show greater training benefits.

7 CONCLUSIONS

Platform motion cues provide the pilot with advanced warning about the subsequent motion of his vehicle which is not available from any of his other senses. This is because the proprioceptive sensors of the body, which are stimulated by platform motion, sense force or acceleration. The eyes can only sense the subsequent motion of the vehicle by way of position changes (or velocity changes in peripheral vision).

If the pilot is required to achieve a performance and control activity in the simulator which is representative of real life, because flying the vehicle is part of the training role of the device, then motion cues become increasingly important as task difficulty and pilot control gain increases. Platform motion is more effective at providing motion cueing than a wide Field-Of-View (FOV) display of the outside world. It is essential when flying in the absence of good wide FOV outside world visual cues: eg due to flying in cloud, in poor weather, at night or with a narrow FOV outside world visual display due to limitations imposed by actual aircraft systems (eg NVGs) or the simulator. Platform motion cues are thus:

- (a) Of comparatively little importance when the vehicle is easy to fly and the required task performance is easily achieved with a low pilot workload and gain: is for largely open loop control of stable vehicles in the presence of strong outside world visual cues and where disturbance motion is either absent or does not require prompt corrective action by the pilot.
- (b) Increasingly important as the task becomes more demanding, and the pilot gain increases, especially in the absence of strong outside world visual cues.
- (c) Necessary for high gain tasks even in the presence of strong outside world visual cues.
- (d) Essential where a pilot must react quickly and correctly in response to some unexpected external disturbance.
- (e) Essential where the pilot is required to stabilise and control a vehicle configuration that has low dynamic stability.

If the pilot is not required to use a similar control strategy and activity in the simulator as in the aircraft, because the principal training task of the device is essentially tactical or procedural, then motion may not be necessary. If flying the aircraft is part of the pilot's total task then the dynamic behaviour of the aircraft mathematical model will have to be incorrect, to compensate for the lack of motion cues, if it is to present a representative workload to the pilot. Clearly such a device should never be used either to train a pilot to fly a given task, especially if the task involves high gain closed loop control over the vehicle, or to give a pilot an appreciation of the handling qualities of his vehicle. Further, care must be

taken to ensure that such a device is never used outside its limited training envelope and that modified flying skills inadvertently learnt on the device are not transferred into flight.

The need for platform motion in a given simulator thus depends on the training role of the device, the handling characteristics of the vehicle concerned, the tasks the pilot is required to fly, the performance he is expected to achieve and the control strategy and control activity he is required to use. The need for platform motion must therefore be assessed for each specific training device based on a detailed analysis of the training required from that device.

8 RECOMMENDATIONS

The training role of every simulator must be clearly specified before its optimum configuration can be defined and, in particular, before the training benefits of a motion platform can be determined. The specification must take account of any likely future changes in the perceived training role of the device, so as not to limit its future use, and must clearly define the limitations of the device so that it is never used outside its valid training envelope.

The relationships between task characteristics, aircraft characteristics, control activity and cueing requirements, especially motion cueing, would benefit from further study. This would improve our understanding of the benefits of motion cueing in the training environment. In particular, it would enable the dynamic behaviour of the aircraft mathematical model to be 'tuned' in the optimum manner in order to give the pilot the same workload in the simulator in the absence of all the cues, especially motion cues, that are available to him in flight.

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17. Abstract This paper discusses motion cueing in piloted flight training simulators, and presents the factors that must be taken into account when assessing the need for, and benefits of, a motion platform so that informed decisions can be taken as to its training value. These factors include the role of the simulator, the handling qualities of the vehicle concerned, the tasks the pilot is required to fly, the performance he is expected to achieve and whether training considerations require him to use a similar control strategy and control activity in the simulator as in the aircraft. <i>Keywords: Flight simulators, Human factors engineering, Flight simulations, Great Britain (SDW)</i>					