AIAA 81-0987R

Improved g-Cueing System

E.B. Bose,* W.P. Leavy,† and S. Ramachandran‡
Goodyear Aerospace Corporation, Akron, Ohio

A g-seat employing both hydraulic and pneumatic systems has been designed. The advantages of this design are much reduced response time, availability of both onset and sustained cues, good high-frequency response, and sufficient excursions to provide vestibular cues in all degrees of freedom except pure lateral translation. The design also features a microprocessor resulting in a self-contained g-cueing system that can be easily fitted into any simulator with minimal changes to the host computational hardware or software, significantly reduced host computer requirements, and a sampling rate of up to 240 Hz without increasing the computational burden on the host simulator. A helmet loader was also designed to supplement the motion cues. The paper presents g-cueing system design details and pilot evaluation.

Introduction

IN recent years, the *g*-seat, in conjunction with other *g*-cueing devices, has become an accepted means of providing motion cues for combat trainers. Although the *g*-cueing system cannot replicate the real-world accelerations and motions because of the limited physical displacements, sufficient motion cues can be generated to enhance pilot training in the simulators.

Recently, Goodyear Aerospace Corporation (GAC) designed a *g*-cueing system for the United States Air Force (USAF) and Royal Saudi Air Force (RSAF) F-15 flight simulators. This paper presents details of the F-15 *g*-cueing system design, cueing philosophy, system performance, and preliminary evaluation. The paper also discusses Goodyear's experience with pilot helmet loaders.

g-Cueing System

The *g*-cueing system provides motion cues through a *g*-seat, a *g*-suit, an active lap belt, and a vibration/buffet system. The conventional *g*-seat uses pneumatic cushions in the seatpan, backrest, and thigh panels to provide acceleration sensations to the pilot. Such an all-pneumatic *g*-seat suffers from several shortcomings, such as lack of onset cues, poor high-frequency response, and insufficient vestibular stimulus that could induce sickness in prolonged air combat maneuver training in the presence of strong visual cues.[1] Further, some all-pneumatic *g*-seats have extremely large response time, as high as 350 ms,[2] leading to poor correlation with the visual system and an unacceptable system lag error. The Goodyear *g*-seat employs a hydraulically driven seatpan, backrest, and lap belt to overcome these shortcomings while retaining the sustained acceleration cue capability of the air cushion.

The *g*-cueing system consists of the following major components: *g*-seat assembly, servocontroller rack, fluid power distribution rack, electronic control rack, and fluid power system. A functional block diagram for the *g*-cueing system is shown in Fig. 1.

Received June 15, 1981; presented as Paper 81-0987 at the AIAA Flight Simulation Technologies Conference, Long Beach, Calif., June 17-19, 1981; revision received Nov. 30, 1981.

*Senior Engineering Specialist, Simulator Product Engineering Department.

†Engineering Specialist, Simulator Systems Engineering Department.

‡Engineering Specialist, Simulator Systems Engineering Department. Member AIAA.

g-Seat Assembly

The *g*-seat assembly (Fig. 2) is the most important element of the *g*-cueing system. The Goodyear system uses a combination of hydraulic and pneumatic systems to provide motion cues representative of the sensations a pilot feels in an actual aircraft ejection seat while under acceleration loads. The attitude of the seatback and seatpan planes are manipulated by controlling the stroke position of linear hydraulic actuators, and the contacting surface on the trainee pilot's body is controlled by varying the pressure within segmented air cushions built into both the seatpan and backrest.

Some of the components of the *g*-seat assembly are directly involved with the generation of the cues, while others are ancillary equipment. These can be classified into categories of active, passive, and functional elements.

Active elements are components of the *g*-seat that have been specially designed or adapted to the *g*-cueing system to produce certain effects or to create conditions peculiar to the simulated environment. Passive elements of the *g*-cueing system are components that contribute to the realism of the cockpit environment by their presence alone.

Functional elements are components that perform specific functions in the real aircraft cockpit and are incorporated in the simulator to create a more realistic environment. For example, the seat height adjustment, which exists in the real aircraft and is duplicated in the simulator, is a functional element. All functional elements must perform identical functions in both the real aircraft and the simulator.

Some elements can have a dual role in the *g*-cueing system. For example, the lap belt is a passive element when it is used to restrain the pilot in his seat. When the belt is mechanically activated to tense or scrub on the pilot's anatomy, creating a cue, it assumes an active role. Other active elements of the *g*-cueing system will be discussed later in this paper.

The typical arrangement of the *g*-seat cueing elements is shown in Fig. 3 and consists of a modified aircraft ejection seat and its accessories, an active seat motion assembly, active backrest assembly, active lap belt assembly, passive survival kit belt, functional shoulder harness, and a functional seat-height positioning mechanism.

The active elements of the *g*-seat assembly are electronically controlled by closed-loop servos that are powered by the hydraulic and pneumatic fluid power systems. The primary cueing elements of the *g*-seat (seatpan, backrest, and lap belt) are controlled linear hydraulic actuators, while the secondary cueing elements (seatpan cushion and backrest cushion) are segmented inflatable cells.

The seatpan surface, underneath the segmented inflatable cushion, is driven in three degrees of freedom (heave, roll,

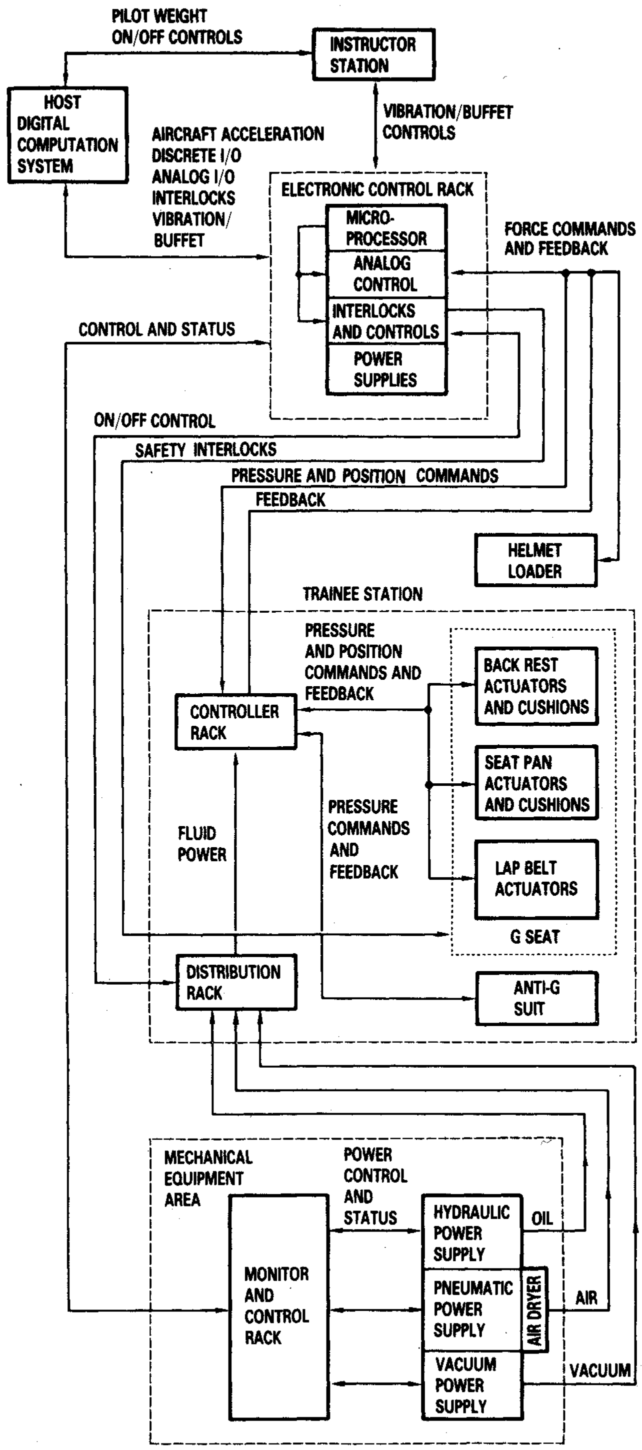

Fig. 1 Functional block diagram of *g*-cueing system.

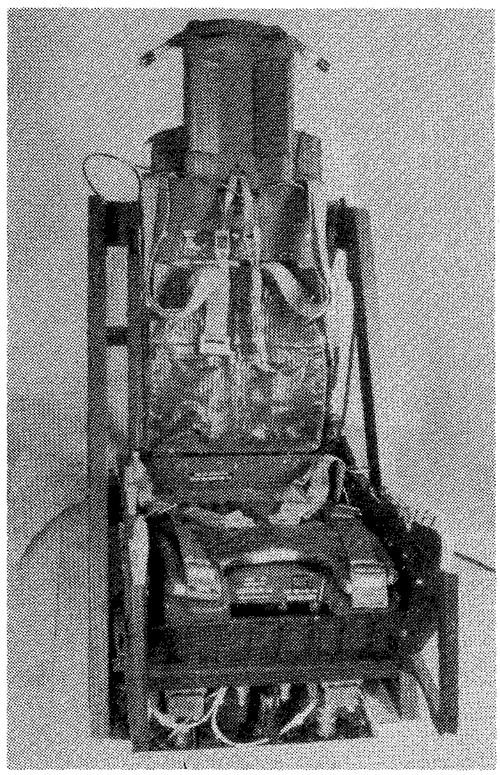

Fig. 2 *g*-seat assembly.

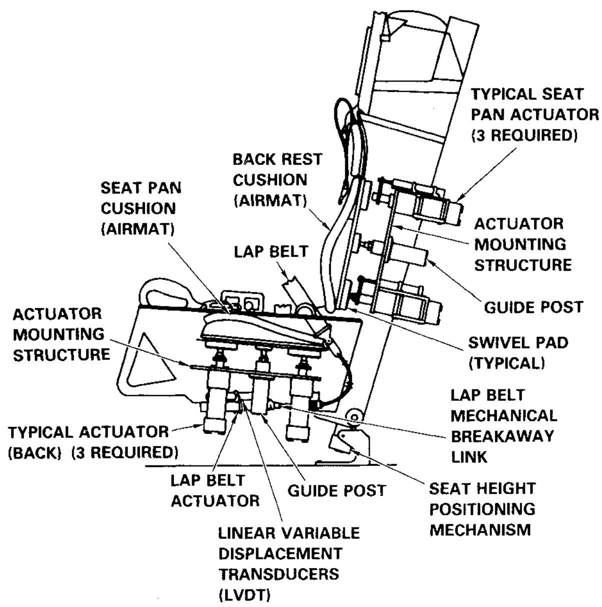

Fig. 3 Typical arrangement of *g*-seat cueing elements.

and pitch). The motion is provided by three hydraulic linear actuators mounted at right angles to the normal plane of the seatpan with excursion that provide ± 1.0 in. of heave travel. Roll and pitch angular excursion is maximized within the constraints imposed by the modified aircraft seat.

The hydraulic actuators provide long trouble-free service by use of self-adjusting rod seals and have pistons designed for minimum breakaway friction. The actuator rod ends fit into sliding swivel pads underneath the seatpan surface that accommodate the attachment point shift when the pan has an angular excursion. A centrally located guide post prevents uncontrolled motion of the seat pan in the longitudinal, lateral, or yaw directions while permitting unrestricted motion in the heave, roll, and pitch directions.

Position feedback for each hydraulic actuator is accomplished by using a linear-variable-displacement transducer (LVDT) which has extremely high reliability, long life, and infinite resolution, and also has no sliding contacts to produce noise, backlash, hysteresis, or wear.

The seatpan motion assembly is designed to be easily removable as shown in Fig. 4a. Hydraulic connections use self-locking quick disconnects and the seatpan motion assembly is capable of being repaired on a workbench. No critical mechanical alignment is required.

An inflatable pneumatic cushion constructed of 1 in. thick AIRMAT® is mounted on top of the moveable seatpan surface. AIRMAT® consists of two layers of fabric, impregnated by an elastomer or resin to withstand pressurization, joined by tie threads extending between the upper and lower fabric surfaces. Since the two layers of fabric are restrained by these tie threads, the g-seat cushion contour does not change shape with the level of pressurization, and the tendency for the cushion surface to balloon is controlled by the length of the tie threads. The pneumatic cushion is divided into a four-cell (segment) arrangement and each cell is controlled by air pressure independent of the other three cells. The combination of the pilot weight on the cushion cells and the internal pressure of the cells determines the amount of pilot body area contact and the resulting sensation of firmness. The initial seatpan cell pressure (1 g level) is selected as a function of pilot weight so that all pilots receive similar area contact and firmness sensations.

Pressure transducers, connected to each of the four inflatable cushion cells, monitor the internal cell pressures to provide for individual closed-loop pressure control. Individual pressure control of the four cells also allows heave, pitch, and roll control.

The pneumatic controller developed to meet the flow capacity and transient response requirements uses a combination of an industrial high-flow, low-friction spool valve controlled by an electric-to-pressure (E/P) transducer. A frequency response of 4 Hz was achieved for the cushion cell pressure which was a fourfold increase in performance over pneumatic controllers being used in aircraft trainers. The resultant pneumatic cushion controller response was a transport delay (to 10% of final value) of less than 0.028 s and a rise time (10-90% of final value) of less than 0.030 s.

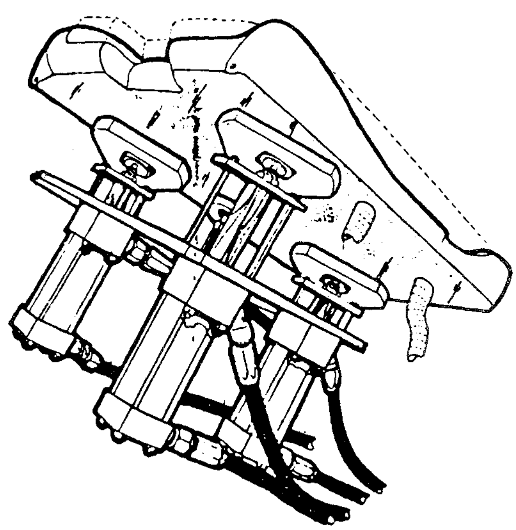

Fig. 4a Seat motion assembly.

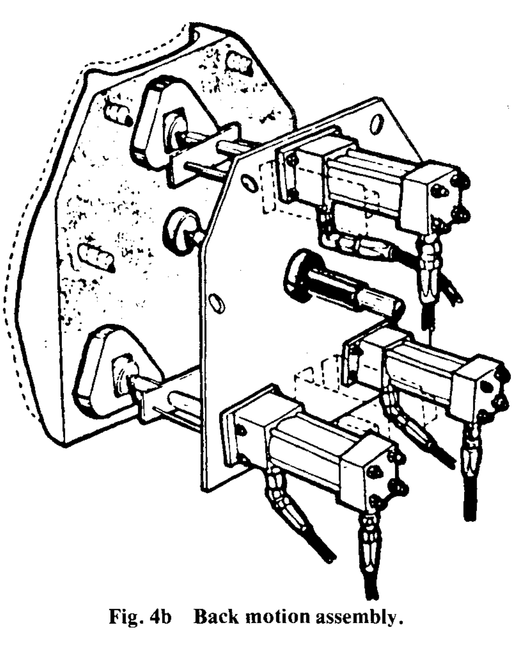

Fig. 4b Back motion assembly.

Passive devices in the form of molded pads or blocks, are incorporated into the AIRMAT® cushion support plate to provide further pressure stimuli to the buttocks. Additional passive thigh wedges are built into the outboard sides of the seatpan cushion to enhance the body contact sensations to the outer thighs during roll or heave maneuvers. Test results indicate that these devices make the pilot subconsciously aware of lateral cues, even though there is no lateral motion of the seat.

The backrest assembly as shown in Fig. 4b is constructed similar to the seat motion assembly. Longitudinal excursion of the backrest linear actuators is ±1.0 in. and the cushion cell excursion is ±0.5 in., resulting in a total excursion capability of ±1.5 in. The backrest assembly provides longitudinal, yaw, and pitch motion.

Both the backrest and seatpan cushion assemblies are attached to their respective pans by Velcro loop and pile fasteners which are adjustable, reuseable, lightweight, and vibration resistant, and which can be fastened blind with no jamming.

In general, the inherent performance capabilities of the hydraulic actuators are used to generate onset acceleration cues, and the pneumatic cushions are used to generate the sustained acceleration cues. Because onset cues are experienced during sudden changes in acceleration (amplitude or direction), a hydraulic actuator is ideal for providing the required response. The hydraulic actuator's response to a step input command was measured to have a transport delay less than 0.010 s and a rise time less than 0.015 s. It may be noted that this response is significantly faster than even the improved pneumatics design discussed above. The hydraulic actuator controllers also have a frequency response greater than 20 Hz.

In addition to the complex composite cues produced by the aerodynamic equations, vibration and buffet cues can also be introduced through the hydraulic actuators. These vibrations consist of combinations of sine wave signals modulated by preprogrammed envelopes generated by the g-cueing mathematical model. The cueing elements themselves are used to provide the pilot buffet and vibration sensations to frequencies greater than 40 Hz, thus eliminating the need for an external seat shaker.

Active Lap Belt Assembly

The active lap belt assembly uses two hydraulic linear actuators, located underneath the seatpan, to position the attachment ends of the lap belt to simulate tightness or looseness of the lap belt. Differential motion of the lap belt attachments provides additional belt scrubbing cue sensations during lateral and yaw maneuver simulations. The addition of the active lap belt to the g-cueing system allows greater versatility to the g-cueing mathematical model programs so that the lap belt cues can faithfully reproduce those sensations experienced in the aircraft, thus increasing training effectiveness. The procedure for using the lap belt is the same as in the aircraft. The pilot enters the seat, buckles the lap belt, and adjusts the belt straps to the desired tension. During simulated flight, as in actual flight, changes in belt tension may be caused by the pilot's voluntary body movements, but further cue enhancement is provided by additional motion of the belt attachment ends as determined by the g-seat mathematical model programs.

***g*-Suit**

The g-suit, in the real aircraft, is part of the pilot's personal equipment and is used to prevent the rush of blood from the brain that could cause blackouts or tunnel vision during high-acceleration conditions. The g-suit as incorporated in the g-cueing system, is used as an active element to provide body pressure discomfort cues that the pilot normally associates with high positive acceleration conditions.

The g-suit servocontroller is similar to the g-seat cushion pneumatic controller. Early pilot evaluations indicated that the g-suit was slow to deflate when it was controlled directly by the vertical g level of the simulated aircraft. This problem was overcome by adding a vacuum system and momentarily forcing the controlling valve to be fully open for deflation based on the sign of the simulated aircraft pitch acceleration.

g-Cueing Processor

A unique feature of the design is the application of microprocessors as part of the g-cueing system to perform all the necessary computations and controls (Fig. 5). The controller microprocessor unit (MPU) is a commercial, fixed-instruction, 16-bit microprocessor designed around a Texas Instrument TM990. This microprocessor serves as an input/output (I/O) and interrupt controller and provides executive control functions for the entire g-cueing system.

The second microprocessor, designated the Arithmetic MPU, is a GAC-developed bipolar, 16-bit, microslice, microprogrammable device that provides the extremely high computation speeds required for the real-time computation application of arithmetic processing. The two microprocessors intercommunicate via shared memory designated as dual function memory. A direct memory access (DMA) card controls the I/O interface between the g-cueing system and the simulator main computer. Digital-to-analog (DAC) and analog-to-digital (ADC) conversion cards are used to translate analog and discrete outputs and inputs from and to the g-cueing servocircuitry. This circuitry consists of the hydraulic and pneumatic servoamplifier cards and a vibration/self-test card.

During g-cueing mathematical model development, a program generation memory card was used to store the g-cueing model until the pilot evaluation phase was completed. It is shown by the dotted line area in Fig. 5. The final g-cueing mathematical model is contained in PROMS that are installed in the arithmetic MPU card which therefore replaces the program generation memory card.

Additional PROMS are installed on the controller MPU card which contains the maintenance programs which are written by GAC for the g-cueing system. The PROMS contain maintenance and test (M&T) routines. During morning readiness, the M&T routines are run automatically one after another and gives a go/no-go result. During M&T, each routine is executed individually upon command to isolate failures down to the card level.

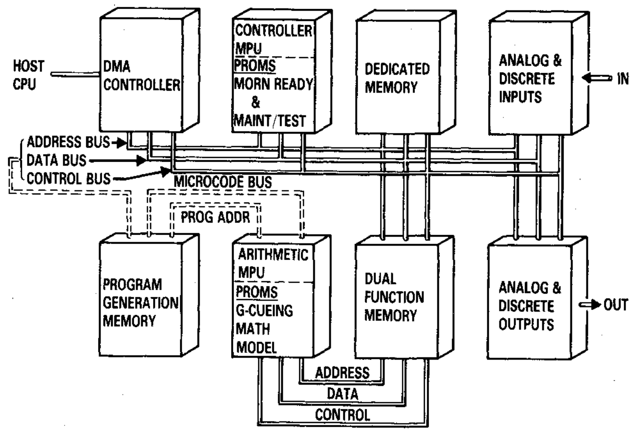

Fig. 5 Microcontroller block diagram.

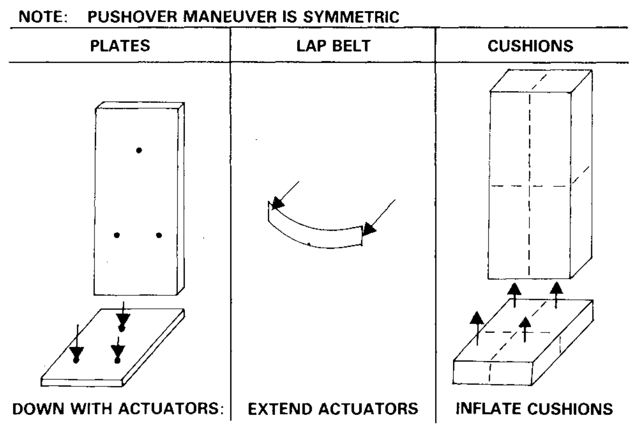

Fig. 6 Cueing philosophy for pullout (positive g).

g-Cueing Methodology

Two opposing g-cueing philosophies exist in the simulation industry: one is that a positive aircraft g loading (pull out) should be simulated by deflating the pneumatic seat cells and the other by inflating them. Both approaches were evaluated at GAC and it was generally agreed by most pilot evaluators that it was more effective if the seat got harder (inflated) as the aircraft undergoes positive g. However, this produced an upward eye-point shift relative to the cockpit displays which is contrary to what takes place in the aircraft. A positive g loading in the aircraft will produce bending and compression of the spinal column. Hence, the approach adopted was to lower the seatpan through hydraulic actuators to provide the downward eyepoint shift as in the real world and inflate the seat to provide firmness of the seat in positive g. Although the required commands are generated simultaneously, as mentioned earlier, the faster hydraulics respond first to provide the onset cues through movement of the seatpan, and the inflation of the cushions follows to give sustained acceleration cues through seat firmness. Figure 6 illustrates the approach for generating vertical cues. A similar approach was used for cues in other degrees of freedom also.

The g-cueing algorithm has the following built-in features:

1) Flexible software. Since the g-cueing system is a very subjective device, it is essential that the mathematical model can be easily adjusted. Any user who has had experience with motion cueing knows of the importance of the pilot evaluation and tuning process. To accommodate this, coefficients are built into the mathematical model to allow for changing the effects of any stimuli on any seat element independently and/or collectively about any axis. This has proved to be very useful during pilot evaluations and subjective testing.

2) Acceleration curve shaping. In order to facilitate an onset acceleration cue, provisions have been made in the software for shaping the stimuli. However, due to the fast response time of the hydraulic actuators and sensitivity of the seatpan, pilot evaluation revealed that the seat was responsive enough to effectively stimulate even the small changes of control positions and throttles without magnification or shaping.

System Performance

Application of microprocessors as part of the g-cueing system to perform all necessary computations offers the following advantages: a self-contained g-seat that can be easily fitted into any simulator with minimal changes to the host computational hardware and software; development independent of the simulator offers cost and scheduling advantages; significantly reduced host computer requirements; and a sampling rate of up to 240 Hz without increasing the computational burden on the host simulator. The last capability is quite significant in reducing total system response lag.

A popular method of measuring overall simulator system response lag error (ΔT_{LAG}) is to apply a step input at the pilot stick and measure the time taken for the system to reach 10% of the commanded response and subtract the time taken in the actual aircraft to reach the 10% point. The 10% point represents the time taken to provide onset cues to the pilot. For maximum simulation fidelity and training effectiveness it is desirable to keep this lag error as low as possible.

Figure 7 shows that in addition to the g-seat itself, additional delays are introduced by: 1) the analog-to-digital converter (ADC) since it will not be possible to synchronize the ADC with an input that could be randomly applied, and 2) the simulator computer frame time to perform flight calculations. It can be seen that the system lag could be reduced by either reducing the computer frame time (ΔT_{CPU}) or by making the g-seat more responsive (reduce $\Delta T_{g\ \mathrm{seat}}$). The first alternative places a great burden on the computation system. Use of hydraulics considerably decreases the system lag since it is faster than pneumatics.

The quick response of the hydraulic servos resulted in roughness-of-motion cues because of stepping caused by the computer iteration sample hold. The solution was to run the microprocessor at 60 Hz and include a 60 Hz notch filter and a 30 Hz low-pass filter. However, all of these (including the microprocessor) introduce additional system lags. Tests were conducted to determine the effect of the filters and sampling rate on the seat performance and a summary is given in Table 1. The evaluations were done both subjectively and by visually analyzing strip chart recordings. However, since the recorder had a bandwidth of about 100 Hz, the sampling effect was not visible above 100 Hz. It may be noted from Table 1 that by eliminating the filters and increasing the sampling rate to 240 Hz a smooth response could be had with a lag of only 14.2 ms. The typical lag error for a pneumatic-only g-seat varies 28-350 ms depending upon the design.[2,3]

Helmet Loader

Goodyear also investigated the feasibility of providing additional cues through the pilot's helmet. The helmet loader uses dc torque motors, strain gage beams, and small cables (Fig. 8) to exert a force on the head and the shoulders. A military-style flight helmet was implemented so that the force-producing cables are essentially attached to both sides of the helmet through linkages on the shoulder straps. Several concepts were tried, but the swivel beam arrangement with the use of suction cups for mounting the device to the helmet and other improvements resulted in less transmission of noise along the force cables and better alignment of the resultant forces. The small hose shown in Fig. 8 was used in experiments to evaluate the need for vacuum assist on the suction cups and was proved to be unnecessary with the helmet GAC was using.

The force exerted on the head and shoulders is proportional to the aircraft Z axis acceleration. For example, positive g accelerations (pullouts) will produce a "sinking" feeling by weighing down the pilot's head while simultaneously lifting (loosening) the shoulder harness. The electromechanical servo loop is a force servo so that the pilot can move his head fore and aft or sideways, with the cable being maintained at a constant tension while being wound or unwound on the drive motor spool.

Pilot Evaluation

The g-cueing system described in this paper, less the helmet loader, is contracted for installation in six F-15 aircraft simulators being manufactured for the USAF and RSAF. The first F-15 trainer with a g-cueing system underwent final acceptance testing in August 1981.

All preliminary studies and evaluations to date were performed on a GAC laboratory prototype system using the F-15 aircraft aerodynamic math model as a driver. The g-cueing system has been evaluated by USAF and Navy pilots and many nonmilitary personnel. Most of the pilots had experience on a six degree-of-freedom motion platform simulator, although not all pilots had flown the F-15 aircraft. Their comments and critiques aided in the refinement of the g-cueing math model. All pilots agreed that their evaluations

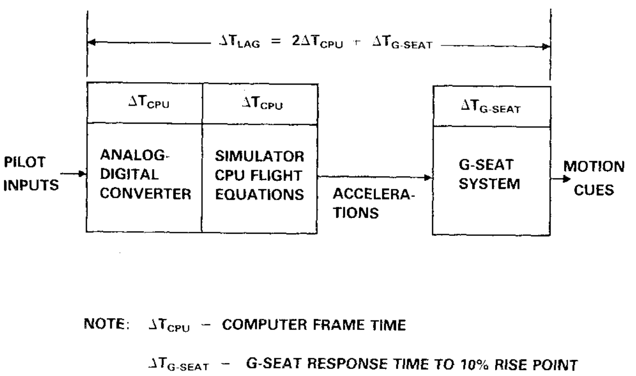

Fig. 7 System worst case lag error.

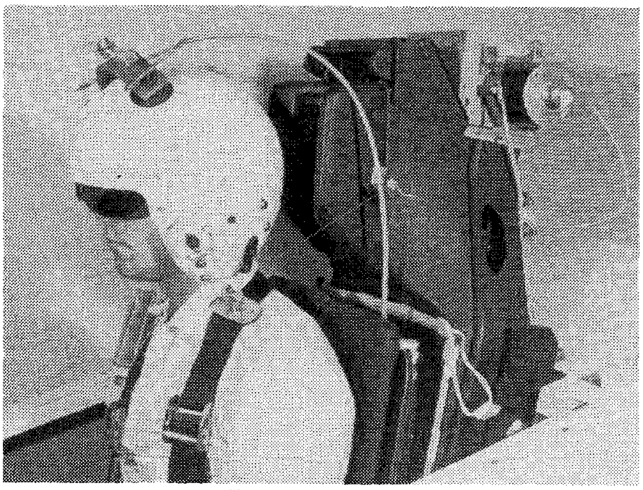

Fig. 8 Helmet loader.

Table 1 Subjective evaluation of g-seat

Sample frequency, Hz	Notch filter	Low-pass filter	Cue roughness	Acceptability[a] (scale 1-10)	g-seat lag ($\Delta T_{g\text{-seat}}$)
60	In	In	Barely discernible	8	37.1
60	Out	In	Discernible, somewhat objectionable	5	33.9
60	Out	Out	Very objectionable	1	26.7
120	Out	In	Not discernible	10	25.53
120	Out	Out	Objectionable	4	18.33
180	Out	Out	Objectionable	5	15.56
220	Out	Out	Threshold of detection	9	14.55
240	Out	Out	Not discernible	10	14.2

[a] Acceptability was based on relative sensing of roughness; 10 on the scale was considered equal to operation without sampling. Five subjects were used.

were highly subjective due to a lack of pre-established guidelines and criteria.

Most of the evaluators were impressed with the capability of the *g*-cueing system in giving them a good jarring. They were complimentary of the excursion range and response capabilities of both the seatpan and backrest. Many of the pilots expressed the opinion that they wanted to get "a good jolt" out of the *g*-cueing system during aircraft buffeting. Opinions were also expressed that the cues were equal to or more than they had received from a six degree-of-freedom motion system, and more than from an all-pneumatic type of *g*-cueing system.

It was observed that the acceleration evaluations fell into several ranges of *g* levels. Less experienced pilots tended to limit their maneuvers to the range of 1-4 *g*. The more experienced pilots, and the F-15 pilots in particular, evaluated the performance of the *g*-cueing system in maneuvers of 4-7 *g*. Each group wanted the cues to be exaggerated to its particular range. The more experienced pilots felt that the cues in the lower *g* ranges should be de-emphasized. Several pilots that flew the same mission expressed divergent views on specific cues. Some pilots felt that the roll maneuver of the seatpan should be reduced, and others indicated that an upper body sway should be added. After evaluating and critiqueing the *g*-cueing system, one pilot admitted that he became more aware of some cues in the real aircraft that he had not noticed before. Most recommendations resulted in changes in the *g*-cueing mathematical model leading to improved performance characteristics.

Before the demonstration rides, some of the evaluators had the preconceived notion that the *g*-cueing system could not be used to replace a seat shaker type of vibration/buffet system. After the demonstrations, most were convinced that they had been wrong. The unanimous conclusion shared by the evaluators was that the *g*-cueing system hydraulic actuation system provides excellent vibration, buffeting, and turbulence simulation without the necessity of providing an external seat shaker. This conclusion was also observed in the tests at Human Resources Laboratory (HRL), Wright Patterson Air Force Base.[4]

Another unanimous opinion expressed was that the active lap belt was a very effective cueing device. There was a difference of opinion as to whether it was more effective to loosen or tighten the belt during the positive *g* maneuver; this will be investigated further during the in-house F-15 simulator pilot evaluations and acceptance tests. Reference 2 has reported the same results during HRL tests at Williams AFB.

Another conclusion reached as a result of the many demonstrations was that it was very important that the antigravity suit properly fit the pilot. It was noted that improperly fitted *g*-suits could prevent effective evaluation of the cueing sensations provided by the *g*-suit mathematical model. Many of the evaluators commented that a slow initial inflation of the *g*-suit could be directly attributed to the fit of the *g*-suit. This conclusion supports the necessity of providing controls at the instructor station to allow adjustment of the point of onset of suit inflation and slope of the suit pressure vs *g*. By adjustment of these controls, proper compensation can be made to tailor the *g*-suit performance to the individual. This problem will probably be minimized in an actual trainer situation since each pilot will be wearing his own personal *g*-suit.

Pilot evaluation included the helmet loader also. The pilots expressed the opinion that the fatigue in the neck and shoulder muscles normally experienced in high *g* aircraft maneuvering over a long period was evident with the addition of the helmet loader to the *g*-cueing system simulation.

There was a consensus among the pilots that the effectiveness or the level of the *Z*-axis acceleration cue was more pronounced through the helmet loader than through the *g*-cueing seat elements. This could be attributed to the fact that the force on the head results in compression of the neck, shoulders, and spine which is not provided by the *g*-cueing seat alone.

Most of the evaluators were surprised to find that they quickly became unaware of the connecting cables and that the cables did not restrict head motion as they had expected. The favorable experience with the helmet loader is in agreement with the positive findings of Ref. 5 which evaluated the effect of helmet loader on pilot performance in a simulated tracking task.

Conclusion

A *g*-cueing system that employs hydraulics for onset cues and pneumatics for sustained cues was designed. This design provides several advantages over an all pneumatic system such as: greatly reduced response time, availability of onset cues, good high-frequency response, and large excursions to provide vestibular cues. Pilot's subjective evaluation and their enthusiastic response to the *g*-cueing system tend to confirm this.

The helmet loader could be very effective in supplementing the motion cues if it can win pilot acceptance. However, presently, lack of enough information on the effectiveness of this device and the psychological resistance to any deviations in the trainer cockpit to the real-world environment have been the main factors for the lack of acceptance. The Military Research and Development Commands must play an active role in promoting the acceptance of the helmet loader among the training commands.

References

[1]Stark, E.A., "Motion Perception and Terrain Visual Cues in Air Combat Simulation," *Proceedings of AIAA Visual and Motion Simulation Conference*, Dayton, Ohio, April 1976, pp. 39-49.

[2]Engel, R.L. and McGuire, D.C., "ASPT G-Seat/G-Suit Optimization," *Proceedings of Interservice/Industry Equipment Conference,* Nov. 1980, pp. 363-369.

[3]Ashworth, B.R. et al., "Objective and Subjective Evaluation of the Effects of a G-Seat on Pilot/Simulator Performance During a Tracking Task," *Proceedings of the 10th NTEC/Industry Conference*, Nov. 1977, pp. 61-80.

[4]Kron, G., Young, L., and Albery, W., "High G Simulation—The Tactical Aircraft Simulator Problem," *Proceedings of the 10th NTEC/Industry Conference*, Nov. 1977, pp. 49-60.

[5]Ashworth, B.R. and McKissick, B.T., "Effects of Helmet Loader on Simulator Pilot Performance," *Journal of Aircraft*, Vol. 16, Nov. 1979, pp. 787-791.