HIGH-G SIMULATION - THE TACTICAL AIRCRAFT SIMULATOR PROBLEM

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SUMMARY

The platform motion system has been the principal motion and force simulation device in the past and over the last five years the G-seat, G-suit, and seat shaker systems have become a part of several of the Air Force's simulators. This paper presents the background behind the development of these devices and a discussion of current and future non-visual system motion and force developments. The challenge of providing high acceleration cues for the tactical aircraft simulator pilot is presented by first, looking at the need for high-G simulation and second, looking at the current development of an advanced G-cuing system, high-G augmentation devices, and bionic means for controlling simulator visual displays.

INTRODUCTION

A considerable body of literature exists concerning the physiological responses of humans exposed to high linear accelerations. The emphasis in much of this earlier work, as reviewed by Fraser (1), Roth (2), Gillies (3), and McElhaney et al. (4), is on the protective measures required to permit subjects to survive transient or sustained high acceleration stimuli and, if possible, to continue performing as pilots. The impact acceleration studies have concentrated on the biomechanical responses and have led to the development of a variety of safety mechanisms. Similarly, the long duration acceleration problem has concentrated on the cardiovascular effects and has led to the development of several G-protective devices, most notably the anti-G suit to prevent pooling of blood in the lower thorax and legs. Research facilities used for these studies have typically been the shaker or deceleration sled for brief duration studies, and the centrifuge for long duration studies. The centrifuge has been used as a way of exposing research subjects and pilots expected to undergo sustained long duration high-G forces (such as astronauts preparing for reentry).

As a simulation tool for training of pilots in practical aircraft, however, the centrifuge has obvious limitations because of the development of very strong erroneous cross-coupled angular acceleration and Coriolis cues during rapid maneuvering, as well as the economical impact of their regular use. Consequently, there exists a clear need with the development of newer tactical aircraft which will develop higher G-forces to find some way of simulating at least some of the effects of these forces on the pilot in order to assist in both the validity of the training and preparation for actual experience in flight.

The principal physiological system responses to plus-G (eyeballs down) sustained acceleration are attributable to biomechanical affects on the skeletal system and cardiovascular responses. The well-known cardiovascular responses are attributable to the hydromechanical forces on the circulation, which produces a relative pressure drop in the circulation varying with height above the heart. The consequences are a gradual draining of blood from the cerebral circulation and the upper body, and a pooling of blood in the abdominal region and in the legs. The most prominent and well-known sensory effects are the visual ones, in which a gradual narrowing of the visual field occurs as delivery of oxygen to the retinal circulation of the periphery is reduced, resulting in an increasing tunnel vision and finally complete blackout which may eventually be followed by unconsciousness. The related cardiovascular responses are associated with the compensatory mechanisms in the system, adjusting cardiac output and heart rate to the new circulatory demands.

The principal biomechanical events noticed by the pilot are, of course, the increase in direct pressure under all supported parts of his body, especially the buttocks and back in a seat, and a tendency for all unsupported parts to be driven "down," requiring a fatiguing increase in steady state muscle tone just to maintain posture. In particular, the unsupported head tends to be rocked back slightly for the typical pilot seat position with the back rest tilted back away from the $+g_z$ vector. The arms, hinged at the shoulder and elbow, are driven down toward the feet, unless they are supported by arm rests and use of a type of side arm controller, in which case there is a pressure buildup under each limb segment. Both total force on body segments and the spatial distribution of such forces are important acceleration cues. As the subject is driven down into his support and the fleshy tissue is compressed, different tactile sense endings come into play. Additionally, changes in the field of view are noted as the pilot's eye position is depressed in the cockpit. The direct biomechanical effect of positive G forces on the respiratory system is in the production of forces on the rib cage which interfere with inhalation and make breathing shallow and labored.

Although a number of other physiological responses to positive acceleration have been identified, the ones referred to above appear to be the most significant from the point of view of simulation for tactical aircraft training.

MOTION AND FORCE SIMULATION DEVELOPMENT

A fundamental control process in which all humans engage is the control of the static and dynamic state vector of their bodies. From seemingly rudimentary skills, such as learning to crawl, to complex tasks such as controlling the activity of powerful and/or high-speed transport machines in which he rides, man employs a remarkably clever set of physiological sensors to maintain his safety and sense of well-being while accomplishing the state vector change he desires. Man learns to discriminate among the physiological stimuli presented him in order to define and refine his perception of bodily motion, and then uses this assessment to modulate his control action. He not only continually mediates the stimuli normally available to him for bodily motion perception, but also likely develops magnitude associations based on variations in the composition of stimuli perceived.

Platform Motion System

The perception of bodily motion is considered important in learning to pilot an aircraft. Hence, in aircraft simulation, the art of providing this perception, motion cuing, is a simulation discipline in itself. The majority of this discipline has centered around attempting to subject the pilot trainee, plus total simulated cockpit, to a reduced-scale semblance of the accelerations associated with the actual aircraft and task. Force-producing devices (motion systems) similar or identical to the device pictured in Figure 1 are employed to present these accelerations as well as provide cues concerning static body spatial orientation. The presentation occurs in all six degrees of freedom and has met with some acceptance, particularly in the simulation of transport aircraft, where translational and rotational accelerations are normally low and aircraft attitudinal changes are normally confined to extremes which do not exceed the motion attitudinal capabilities by more than a factor of two or three (5). The Air Force is currently not including platform motion systems for the A-10 and F-16 simulator programs.

The single strongest asset of a motion system is that once in the simulated cockpit, the pilot is presented with a force and spatial attitude generation system which, in terms of visual appearance, usually is entirely faithful to that existing in the actual task. Simulation engineers working closely with pilots note that such visual environmental fidelity seems important toward enabling the pilot to "slip" into believing he is in the actual task so that he will react in the same manner as in the actual task. Visual environmental fidelity is afforded by the motion system because the total cockpit and pilot are moved, and thus vestibular response is excited through the same mechanism as in the actual task, pilot/cockpit inertial coupling exists, and associated somatic sensation occurs naturally without artificial devices. Unfortunately, motion systems are constrained by the necessary physical limitations placed on their size (6). As the dynamic range of the desired force sensation increases and/or the duration of desired force application increases, these limitations become more apparent in the simulation. For medium-performance tactical aircraft simulation, the motion system simulation engineer must make increasing use of onset cuing plus subsequent washout, wherein only the leading edge of the simulated aircraft acceleration is presented to the pilot trainee, followed by a low-level period wherein velocity and excursion capability expended during the onset is recaptured in preparation for the next cue. The crux of the simulation engineer's dilemma

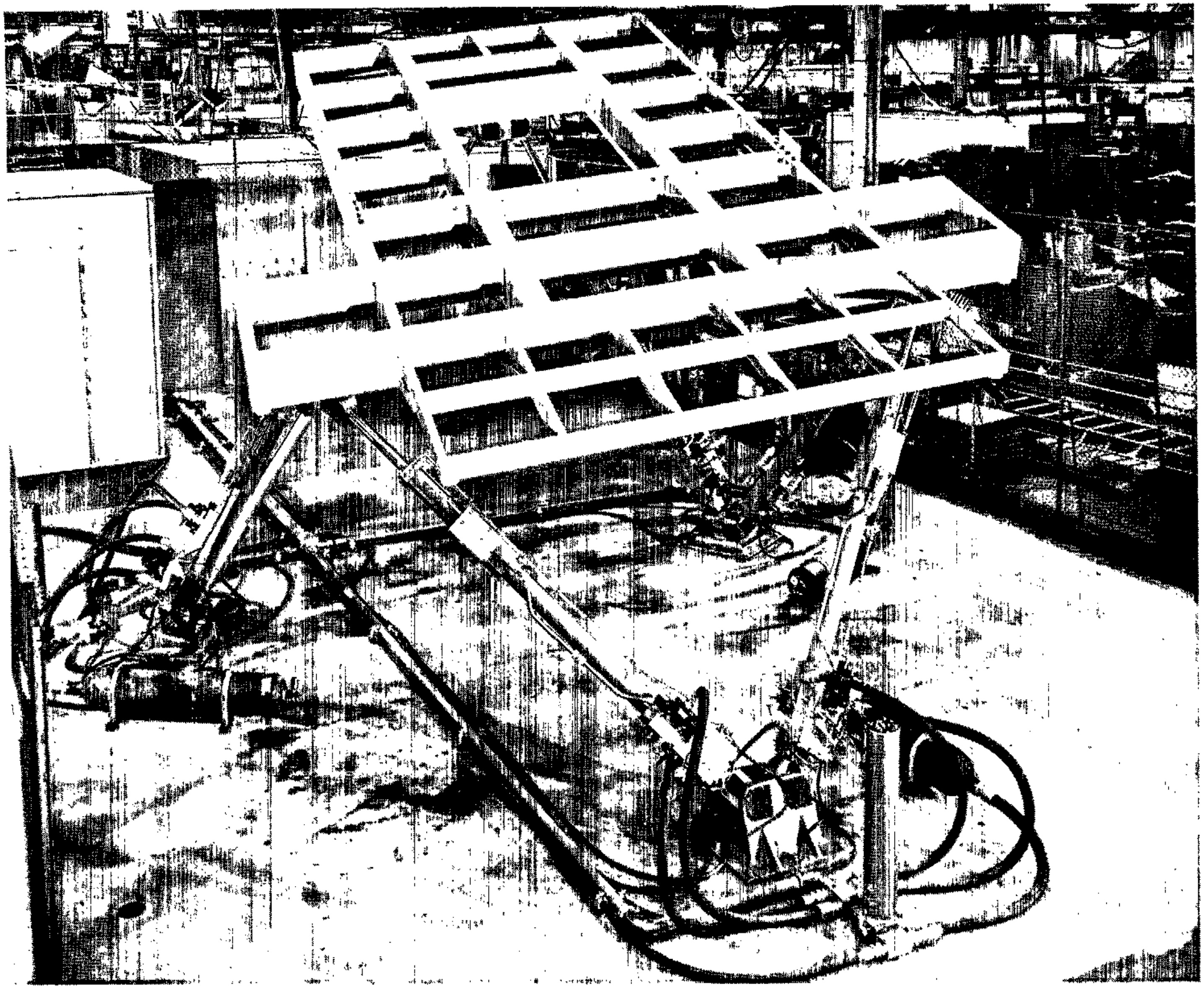

Figure 1. Six Post Platform Motion System - Link Division of Singer

is that as he tries to increase the duration of force application, the permitted cuing dynamic range decreases, and vice-versa.

The dilemma arises because in moving from transport to tactical aircraft simulation, both desired force duration and dynamic range increase. Under these conditions it is reasonable that stronger, more pronounced physiological perceptions should be available to the pilot from the somatic sensory system owing to stronger body/cockpit inertial coupling. Should both acceleration duration and magnitude become even larger, as in the newest tactical aircraft, the frequency of occurrence of physiological effects associated with high-G conditions is likely to be more prevalent, and it is not unreasonable to extrapolate that these perceived effects will find their way into the control patterns employed by the pilot. It is apparent, then, that the physiological conditions desired within the simulation begin to outdistance the capability for cue production through utilization of the motion system alone. However, the motion system appears to have a useful range for physiological stimuli production beyond which additional devices must be brought to bear.

G-Seat

The Air Force Human Resources Laboratory recognized this fact in the late 1960's during the study phase preceding the Advanced Simulation in Undergraduate Pilot Training (ASUPT) contract. A commonly accepted conclusion at that time was that in pursuing the development of force stimuli simulation devices ancillary to the motion system, first importance must be given to the accurate reproduction of somatic stimuli associated with the effects of acceleration in the 1 to 3 G-range; simulation of induced visceral effects attendant with higher acceleration regions would follow at a later point in time. The logical candidates for somatic stimulation were those physiological systems which could be addressed through pilot seat alteration, since there was a reasonable chance to maintain good cockpit visual environmental fidelity if the simulation was confined to the seat itself. Further, it is quite apparent that a large part of the somatic sensation in the actual aircraft occurs in the buttock/back region as a result of pilot/seat inertial coupling effects.

Link Division of the Singer Company developed the G-seat (7) pictured in Figure 2 under the ASUPT contract for the express purpose of determining the adequacy of simulating tactile, pressure, and skeletal stature stimuli associated with flight-induced body G loading. The approach selected involved construction of seat cushions composed of mosaics of elements in which the elevation of each is individually controlled by the drive philosophy programmed into the simulator's computational system. It is therefore possible to change cushion attitude, elevation, and shape with the same mechanical system. The G-seat employs a variable-tension lap belt to apply pressure stimuli in the ventral area of the pilot during negative G and/or braking conditions, the G-seat drive philosophy developed by Link primarily addresses the skeletal attitude shifts and their impact on eyepoint perspective, head/neck bobbing, and flesh scrubbing as well as localized flesh pressure changes and tactile perceived area-of-flesh/seat contact changes associated with sustained G conditions. Experimentation with this seat indicated that not only were the sustained G stimuli presented by the seat employed positively by pilots in the control of the simulated aircraft, but in moving from one acceleration magnitude to another, a form of acceleration onset information was provided to the pilot. The two ASUPT G-seats were the first of ten similar "First Generation" G-seats built or currently under construction for use by the Air Force and Navy. During this period, the value of the G-suit as a G-cuing device has become more broadly appreciated.

G-Suit

The G-suit cue represents an excellent example of apparent pilot G-level assessment by way of association. G-suits are employed in tactical aircraft to counter blood pooling in the lower extremities during high-G conditions. Providing external pressure to the lower extremities, the suit restricts the blood from settling under inertial forces and thereby maintains more normal blood pressure conditions at the heart level and, more importantly, retards blood starvation at the elevation of the brain, thereby extending either G-level range or exposure time prior to loss of vision and subsequent unconsciousness. A predominant early perception experienced by the pilot, well before any visceral effects materialize in vision, is a tactile perception associated with the pressure induced by the G-suit. The pilot appears to associate this perception with increased G loading. Providing a similar experience within the simulation by inflating operationally issued G-suits according to the simulated flight G loading produces a very strong G loading cue for pilot utilization. Equally important is the fact that this cue is made available by a device

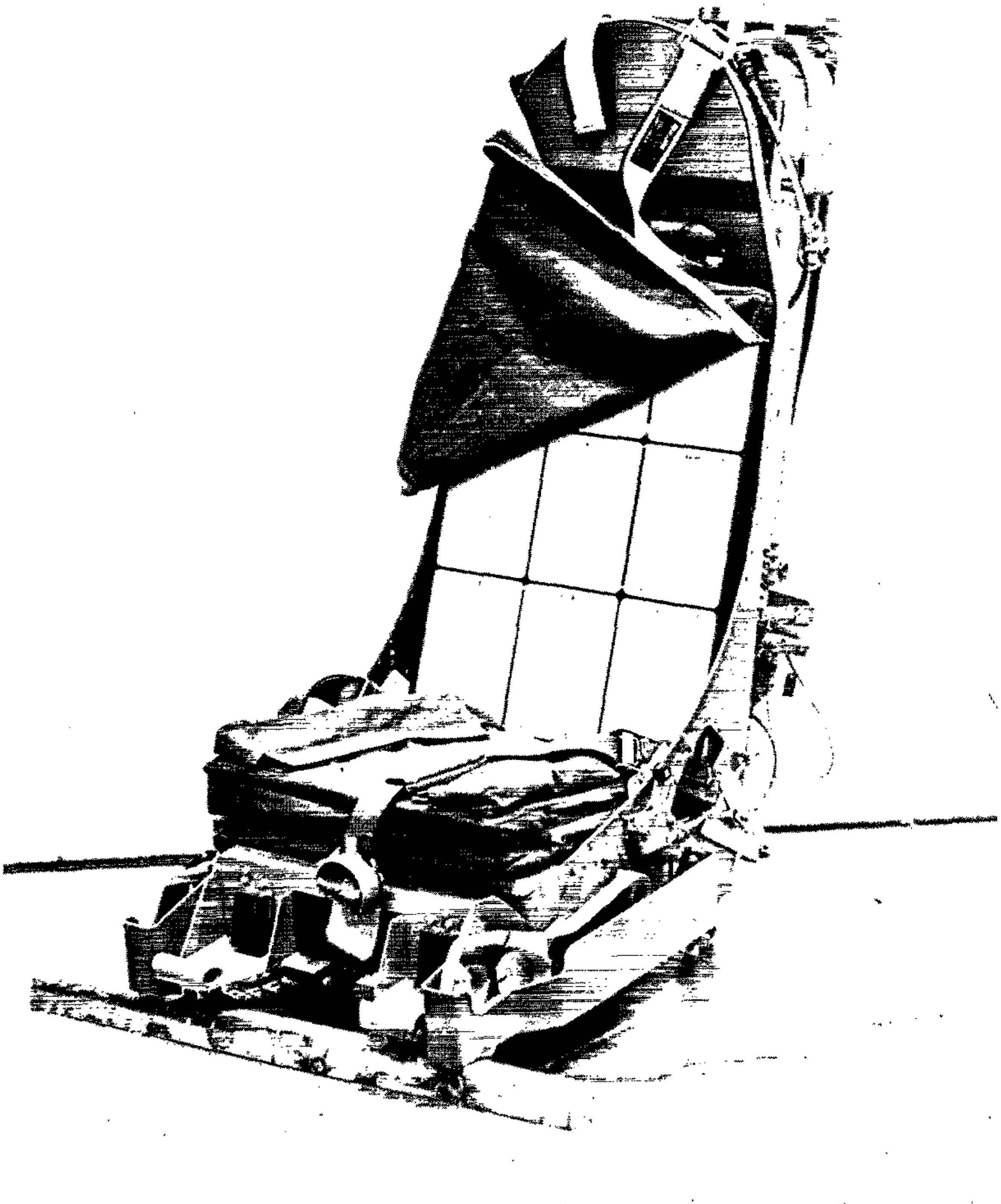

Figure 2. First Generation G-Seat (Backrest Bellows Exposed)

which is present in the actual task, and, therefore, visual environmental fidelity is maintained within the simulation.

Seat Shaker

Coincident with G-seat and G-suit utilization, seat frame shaker systems have been developed to provide vibratory cues in the frequency range beyond that readily obtainable with cockpit motion systems. Vibratory cues are a part of the force environment somatically monitored by the pilot and used within his control patterns. Much as any large machine, an aircraft "talks" to its pilot through vibratory means, providing information concerning its operation and its status within the realizable flight envelope. In terms of G-cuing systems, if the motion system is labeled the low-range device, the G-seat, suit, and shaker systems would be considered mid-range G-cuing systems.

Limitations and Ranges of G-Cuing Devices

The successful introduction of the G-seat within the tactical aircraft simulation environment has been an extremely significant milestone in terms of mid-range G-cuing. However, just as the motion system has its limitations, so does the G-seat. As previously mentioned, the G-seat confines its physiological stimuli production to the pilot/seat inertial coupling area. It makes no demands upon the pilot other than to sit in the seat and buckle the strapping used in the seat and in the actual aircraft, thereby maintaining visual environmental fidelity. As a consequence of this approach, pressure buildup in the back/buttocks area is limited to that available from the 1-G weight of the subject himself as modulated by variation in the shape of the flesh-supporting surface. Neck muscular stimuli associated with G loading of the helmet and head are limited to those available by changing the attitude of the torso so that the 1-G gravitational weight of the helmet/head loading varies neck load. Head bobbing through interplay of skeletal structure and cushion surface attitude is limited to that range of attitudinal change permitted as complementary by the somatic senses of the back/buttocks area. Inertial load buildup in the arms is not directly addressed. Visceral effects and their perceivable by-products are ignored altogether. Yet as the dynamic range of aircraft acceleration increases, as it has with the introduction of advanced fighter aircraft, it is not unreasonable to hypothesize that future force simulation systems must include some of these high-G effects.

The development of kinesthetic cuing devices can be likened to the development of a speaker system. As the range of information to be transmitted increases or its composition changes to include new pieces of information important to be heard, the transmission device must be altered. In some cases the device is designed to address specific characteristics and cannot adequately cover the complete spectrum of information to be transmitted. In speaker technology the answer has been to employ different speaker designs in the area of their respective merit but collectively as one integrated system: low-range woofers, mid-range speakers, and high-range tweeters. A corollary may exist in kinesthetic cuing devices when examining the merits and limitations of motion systems and G-seat systems. Advanced fighter aircraft extend and change the composition of kinesthetic cues to be delivered. The high-G augmentation devices discussed herein may be considered as independent operators and would be designed to provide specific sensations. Their true merit, however, lies in extending the spectrum of information transmission when used in conjuction with G-seats and motion systems.

ADVANCED G-CUING SYSTEM DEVELOPMENTS

Advanced Low Cost G-Cuing System

The introduction of the first generation G-seat to the tactical aircraft simulation environment demonstrated the apparent potential for inducing valuable kinesthetic stimuli via a direct approach to the somatic sensory system. However, questions arise as to whether the mechanical capabilities of the first generation G-seat optimally exercise this potential and extract a maximum benefit from this cuing source. Can improvements in selected areas increase the cuing yield and if so, what areas and what type of improvements should be considered? In 1975, the Air Force released a specification defining G-seat requirements for future G-seat procurement. Additional G-seat research is required to establish a baseline system reflecting optimum performance capabilities. These capabilities would then be included within and modify the specification controlling G-seat procurement.

One point of particular concern in any cuing system has been system response (8). The first generation G-seat employs a servo system of approximately 1 Hz bandpass. Initially, a fairly low software iteration rate in the 7 1/2 - 10 iterations/second range were employed to drive the G-seat. Although under certain sharp maneuvering conditions there is occasional pilot comment noting apparent time delays in the seat system, it is not known whether this is purely a consequence of the iteration rate or whether improved hardware response would be of material benefit. Iteration rate alteration research at the installations currently employing G-seats is not easily accomplished. Facility computational capability constraints are encountered because the iteration rate to be altered is not only the G-seat software but usually the complete flight dynamics package as well. To establish the most beneficial response requirements, it is advisable to employ a computational facility within which flight dynamics and G-seat software can be cycled at rates in excess of that thought to be the maximum required and employ seat hardware possessing high response characteristics. In this manner, full system capability can be degraded to determine that point at which further degradation produces adverse and noticeable system delays.

The first generation G-seat was designed to provide a sensation of sustained acceleration and employs a cuing philosophy which does not make use of transient onset cuing (7). This approach has been well received as a sustained cuing device and, somewhat unexpectedly, it was found that a measure of onset cuing is overtly experienced as a by-product of the sustained cuing philosophy. Nevertheless, ongoing work in sensory systems modeling indicates that improved kinesthetic cuing should be attainable through more sophisticated transient cuing drive schemes. Again, it is desirable, when considering transient motion, to employ highly responsive hardware as the initial starting point and experimentally degrade the response to that level wherein transient cuing concepts are noticeably and adversely affected.

With the foregoing in mind, the Air Force Human Resources Laboratory concluded a G-Cuing System research test bed was required and in mid-1976 awarded Link a contract for the development of an Advanced Low Cost G-Cuing System (ALCOGS) embodying certain specific objectives:

1) Bring seat, suit, and shaker together as one integrated system with common control.

2) Improve the response characteristics of primarily the G-seat, and secondarily the G-suit, over those existing in today's operational seat/suit systems.

3) Provide closed-loop servo operation so that accurate means to measure system capability expended to produce a given cue can be monitored.

4) Investigate, develop, and embody within the final system mechanical concepts which improve the somatic cuing quality of the G-seat over that available in the first generation of G-seat approach.

5) Broaden the resultant hardware and software design to accommodate F-16-type tilt-back seat configurations as well as the more conventional upright seat configurations associated with the F-15 and other aircraft.

6) Attempt to design this system so as to lower the aggregate cost of a seat/suit/shaker system.

7) Build and deliver a system with the above characteristics as well as a software drive module for Air Force research.

The ALCOGS system has been designed and is currently under construction. An artist's rendition of its seat configuration is provided in Figure 3. The most noticeable changes from the first generation G-seat are:

1) The departure from a mosaic element cushion approach, but the retention of cushion attitudinal and elevation change capability.

2) The implementation of thin cushion surface bladders for localized pressure and tactile area-of-contact stimuli generation.

3) Hydraulic actuator servo systems to provide the desired response characteristics.

4) Adoption of passive rather than active seat pan thigh panels.

5) The implementation of lower backrest radial elements to provide strong area-of-contact cues for vertical and longitudinal acceleration.

6) Differential lap belt drive for inclusion of lateral as well as longitudinal and vertical belt cuing.

7) The addition of a seat pan longitudinal degree of freedom cascaded on seat pan cushion pitch roll and heave.

The ALCOGS G-seat cushion assemblies are

Figure 3. Advanced Low-Cost G-Cuing System (Artist's Concept)

mounted in a replica of the F-15 seat frame which in turn is mounted on a test bed frame which can either be inserted in a T-38 cockpit or left free standing external to the cockpit. The seat frame is supported on the test bed frame by linkages which permit the seat to be oriented at any angle of inclination between that employed by the F-15 and F-16 seats. The seat frame is pinned to the test bed so as to permit the frame to be vibrated by a seat shaker actuator at ± 1/2 G in the 4.5 - 40 Hz range. Buffet and other vibratory effects may be displayed by the seat frame shaker or, alternately, the seat pan cushion itself. The suitability of the latter will determine if the role of the seat frame shaker may be absorbed by the G-seat and the seat frame shaker system eliminated from future G-Cuing Systems.

The G-suit features a press-to-test and pressure/G instructor input which are handled all-electronically rather than by mechanical and software means, respectively. A high volume pneumatic servo valve design serviced by compressed air and vacuum provide more rapid suit pressurization and exhaust than that available, for example, in the Simulator for Air-to-Air Combat (SAAC) and F4E18 G-suit installations.

Similar to many motion system installations, the G-Cuing System is supported by an electronics control cabinet which houses the electronics associated with system control logic and the sixteen servo loops. The Electronics Control Cabinet permits system operation in a "maintenance" mode wherein the G-Cuing System servos may be driven manually, or by two software drive modes: one wherein system control is maintained at the location of the electronics cabinet and a second wherein system control is transferred to a remote location such as a simulator instructor/operator station. The electronics cabinet employs two variable frequency oscillators to permit the generation of superimposed vibratory effects at any frequency in the 4.5 to 40 Hz region. A discrete "bump" channel is further superimposed upon the vibratory output. The electronics cabinet also controls the activity of the G-Cuing System pumping station wherein hydraulic, pneumatic compressor, vacuum pumps, and associated reservoirs are located.

Primary design problems centered in the G-seat system and in two areas: system response and packaging. Two G-seat design objectives called for seat pan and backrest cushion excursion of 2-1/2 inches and a rise time of all servo actuators of 30 ms or less. The latter implies a system bandpass of 10 Hz or an order of magnitude larger than that available in the first generation G-seat. The bandpass objective advocates the utilization of hydraulic actuators and, to ensure that hydraulic resonant frequencies are maintained well above the bandpass frequency, servo valve mounting in close proximity to the actuator. The servo valve/actuator selected meets the 10 Hz bandpass objective.

Even more challenging, the same 30 millisecond rise time objective was sought in the cushion pneumatic surface bladders (firmness bladders) overlaying both seat pan and backrest cushions. A dual compartment (right and left) bladder is employed on the seat pan and a single compartment bladder employed on the backrest. Although only approximately one inch thick when inflated, these bladders represent significant volumes. Based on the function of the bladders, pressure and tactile area of contact stimuli generation induced by depressurization and resultant flesh contact with the undersurface supporting the bladders, it was felt the driving medium must be air. After considerable searching and testing, a two stage pneumatic servo valve assembly was developed which can handle the large air volume at the desired 30 ms rise time objective.

It is apparent that the response design objective required the utilization of servo actuators considerably more mechanically sophisticated than that employed in the first generation G-seat. System cost reduction could be realized, therefore, only if the cushion assemblies could be packaged in such a manner as to permit a broad application to many different seat styles with minimum redesign. A design objective then was to package the cushion assemblies within volumes commensurate with that extant in standard survival kits and parachute packs. This task was made difficult by the number of actuators employed, the fact that these actuators are hydraulic, the desire to keep actuator and servo valve in close proximity to one another, and the 2 1/2-inch cushion stroke requirement coupled with ram end cushion capability. The resultant design packages five servo systems in a backrest assembly which is approximately 15 x 21 x 3-3/4 inches in dimension. The seat pan assembly packages six servo systems in a volume approximately 15 x 15 x 6 inches in dimension. A modular design approach has been employed in the actuator assemblies themselves in order to permit actuator set up and service.

The ALCOGS system will be integrated with the Wright-Patterson AFB Human Resources

Laboratory Simulation and Training Advanced Research System (STARS) complex and it is expected that G-cuing research will commence utilizing this system prior to the end of 1977.

High-G Augmentation Device Study

As mentioned earlier, the G-seat may be considered a mid-range G-cuing device. Newly developed tactical aircraft exercise a flight regime wherein high-G loading is more often experienced and the physiological stimuli associated with this condition may gain importance in aircraft maneuvering control patterns. Based on this, it is appropriate to commence consideration of the types of simulator systems which might provide high-G effect stimuli.

A combined Human Resources Laboratory/Massachusetts Institute of Technology/Link effort is currently studying potential force simulation systems in an attempt to identify those systems which:

a. are likely to produce a stimuli important to high-G maneuvering control and,

b. appear to be able to generate stimuli artificially in a 1G environment by means acceptable to operational pilots.

The current effort is strictly a study leading to characterization of the type of hardware/software systems required to produce the desired end effect. The system characterization is to form the foundation for eventual construction of experimental systems to determine the adequacy and usefulness of the simulation stimuli source.

The study will attempt to set forth the most reasonable methods of generating G loading stimuli in the following areas:

a. Shoulder harness

b. Head/helmet coupling

c. Limb loading

d. Aural effects

e. Visual effects

The effort in addition to addressing the above specific areas will investigate the potential of stimuli production via some of the following methods:

a. Body negative pressure

b. Respiratory control

c. Lacrimation control

d. Flesh pressure/temperature interrelationships

Bionic Control of Simulator Visual Displays

Bio-feedback techniques are also being considered for the tactical aircraft simulator pilot. The University of Dayton is currently developing for the Air Force a method for bionic control of the simulator cockpit visual environment.

The objective of this effort is to improve a technological deficiency which currently exists in training simulation. Gravity effects are simulated in ground-based trainers via motion systems, G-seats, G-suits, seat shaker systems, and visual cues. All of these G-cue effect devices have their strengths and weaknesses. This effort will address the gravity effect produced by current visual simulation systems. State-of-the-art training devices have the capability for dimming the visual display of the simulator as a function of positive G. This effect simulates the loss of vision pilots sometimes suffer under high, positive acceleration. The Simulator for Air-to-Air Combat (SAAC) is a good example of this technology. The problem with this simulation is that the pilot has no physiological control over the (1) intensity and (2) onset of this dimming in the SAAC. He cannot, for example, perform the M-1 maneuver and eliminate the dimmed display; he has no direct means of affecting the display in the simulator other than changing angle of attack, etc. In the actual aircraft, however, the pilot can control the loss of vision through the M-1 maneuver. The purpose of this effort is to develop a means by which pilot straining, via the M-1 maneuver, can be sensed and used in the total simulation control loop to drive the dimming level of the visual display as a function of G. Such a development should enhance the tactical air combat simulation and provide valuable training in pilot energy management.

This effort encompasses the design and development of a software program and associated hardware for the bionic control of acceleration induced dimming of the simulator pilot's visual display. To accomplish this, two algorithms will be developed. One will be a dynamic algorithm of the human visual system which will be driven by the pilot's G-environment. The other will be an algorithm to predict the effectiveness of the pilot's M-1 maneuver, which will be driven by electromyographic potentials from selected muscle groups. The outputs from these two algorithms will be integrated to drive a brightness controller for the visual display. The integrated system will be implemented at the AFHRL STARS facility on the T-38 simulator. If successful, the system may be implemented on the SAAC, UPT-IFS, and other Air Force simulator programs.

CONCLUSION

The successful introduction of the G-seat within the tactical aircraft simulation environment has been an extremely significant milestone in terms of mid-range G-cuing. However, just as the motion system has its limitations, so does the G-seat. With the possibility that the A-10 and F-16 simulators will have no platform motion systems, the Air Force Human Resources Laboratory is performing the research and development of other means of full-range G-cuing. High-G augmentation devices are being designed to provide those specific sensations characteristic of fighter/attack aircraft. An advanced G-cuing research system has been developed which can address the A-10, F-15, and F-16 motion and force simulation problems. However, the true merit of these and other devices lies in their ability to match the spectrum of kinesthetic cues delivered in advanced tactical aircraft.

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