MOTION SIMULATION ENHANCEMENT: THE DEVELOPMENT OF A RESEARCH G-SEAT SYSTEM

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INTRODUCTION

The methods by which man learns have long been the subject of research; the interim findings, observations, and theories have often been the subject of much controversy and argument. Fundamental agreement exists, however, that man must have contact with his environment; he must be aware of the stimuli about him and he must interpret them and act upon their informational content. An important portion of learning and training research, then, is directed at obtaining and understanding of how man relates to, and with, his environment.

Man's sensory systems are the interface between him and his environment; through these systems travel the raw information used in learning and in the maintenance of task proficiency. Considerable effort has been expended on assembling a knowledge of the operation of the various sensory systems, with various degrees of success, depending upon which sensory system is under consideration. The knowledge derived from the visual sense, for instance, appears to be more precise, more formalized, and less subject to question than that derived from the vestibular sense and, to a greater degree, the body awareness sense. Simulation, a technique employed for training, depends heavily on the role sensory systems play in the learning process.

Historically, the simulation devoted to providing stimuli to be used by a given sensory system appears to generally follow the knowledge existing at the time pertaining to that sensory system. Hence, the simulation of the visual scene, first in terms of cockpit instrumentation, and later the window visual scene, is quite sophisticated and refined. Stimuli for the vestibular and the kinesthetic senses were provided through the use of various types of cockpit motion systems. Most recently, stimuli for sustained accelerations are being provided for in the development of G-seats.

Work continues in all areas of sensory simulation to determine which stimulus channels have priority within specific training tasks, and which seem to have low priority and do not noticeably degrade the learning process when omitted. Included in this effort is investigation of intra and inter-sensory system cue reinforcement and the question of partial or total cue substitution. The investigation or the interrelationship of motion information available through the vestibular and the haptic, or "body feel", sensory systems has lent emphasis to the development of G-seat mechanisms suitable for producing the type of stimuli recognized by elements of the haptic sensory system.

PRELIMINARIES

SYSTEMS FOR MOTION PERCEPTION

It is helpful, at this point, to briefly discuss the elements of the system by which an individual perceives and evaluates the type of motion to which he is subjected. The sensory systems involved are not limited solely to the transmission of motion information. They are also involved in ascertaining the direction of gravity with respect to the head, the relative attitude of the skeletal structure with respect to that gravity vector, and the location of the surface of the flesh with respect to the skeletal attitude.

Man is thought to perceive motion through at least three basic sensory systems: they are the visual, vestibular, and haptic systems. The visual sensory system will not be discussed herein but is mentioned as one of the sensory systems entrusted with the important task of kinesthetic determination.

The vestibular system, located in the inner ear, is the best known motion sensory system. The semicircular canals, the primary sense organs of this system, are two sets of three fluid-filled hoops which are oriented so that the planes of the hoops lie normal to one another, thereby forming an equivalent axis system. When the body is subjected to acceleration the fluid moves in the canals and passes through hairlike detectors which signal the movement to the brain.

Another portion of the vestibular sense deals with that of gravity vector orientation detection. Herein the utricle is considered the primary sense organ and is filled with a fluid in which are immersed small particles, of higher specific gravity than the fluid, called otoliths. The positions assumed by the otoliths on the hairlike inner surface of the utricle are responsible for gravity orientation detection.

A third sense organ of the vestibular system is the saccule. Little is known of the functioning of this organ; however, it is thought to contribute to the sense of balance and orientation.

Elements of the haptic sensory system are employed in kinesthetic determination. The haptic system, a lesser known and far from formalized system, deals in part with the perception known as "body feel". The elements, including the senses of touch and temperature, pressure sense, muscle sense, and skeletal joint sense, seem unrelated when viewed individually but appear to have some common relationship when viewed from the position of kinesthetic determination.

MOTION AND THE HAPTIC SYSTEM

As mentioned earlier the haptic system mediates the body feel of motion. It seems reasonable to assume that the greater the acceleration to which an individual is subjected, the larger or better defined the haptic system response. Of initial concern, then, are large sustained accelerations such as those found when a pilot of an aircraft performs a tight dive pullout.

Consider the dive pullout case in which a pilot is subjected to a "g" loading or increase in apparent body weight, proportional to the number of g's of acceleration experienced by the aircraft. Assuming the pilot is seated, we might expect his head, neck, and upper torso to compress along the spinal axis, his shoulders to droop under the "added" weight of his upper arms, and his buttocks to sink deeper into the seat cushion, thereby decreasing the included angle between upper and lower legs. In other words, his body orientation would change slightly due to the increase in apparent weight.

Furthur, we might expect our subject's flesh to droop and change the loading characteristics of the muscles and, corresponding to the increased apparent weight of upper torso, we would expect an increase in buttock flesh pressure. Vascular system pressure increases in the lower torso and legs would be experienced, and visceral effects of internal organ distention and body fluid pressure changes could also be expected.

Now, if the acceleration vector had significant components in the plane normal to the subject's spine, the subject would begin to react like an inverted pendulum. Head, shoulders, and upper torso would tend to pitch or roll about the lower torso, again changing skeletal attitude and muscle loading conditions, to say nothing of the obvious shift in eye point. Such pitching and rolling is significantly reduced through the use of lap belts and shoulder harnesses; however, these restraints do not remove the inverted pendulum effects of the head and neck, only partially restrain shoulder movement and, in general, introduce a new set of body points subject to touch and pressure sensation.

Haptic system elements are employed in perceiving these physiological changes. Most of these changes manifest themselves in one or more of four modalities: skeletal attitude changes, muscle tonal changes, pressure changes, and touch or area of contact changes. Considering first skeletal attitude changes, the older, more formalized theory advocates that joint receptors are interspersed throughout the ligaments and capsules of the skeletal joints and are responsible for monitoring the attitude of one bone structure with respect to its neighbors. The receptors themselves appear to be attitude-critical; at any given joint angle a particular set of receptors triggers the neural response, becoming more and more passive (adapting) until that particular joint angle is again approached, while other sets of joint receptors become active as the joint angle passes their particular critical stage. In this manner the attitude of the structure is perceived, via successive joint relations, relative to the spine, to the neck and head, and finally to a basic reference frame such as the gravity vector. Thus the shift in skeletal alignment due to G loading produces an informational input in the kinesthetic evaluation process.

Not everyone subscribes to the presence of joint receptors. An emerging theory challenging the presence of joint receptors is predicated on the belief that joint attitude perception is the product of differentiation of pressure sensations resulting from deformation of the flesh surrounding the joint.

A second category of haptic sysem receptors are the receptors located in and around the muscles, which are generally thought to be of two types: the spindle and tendon receptors. The spindle receptors appear to possess two subsets of receptors. The more numerous primary set, characterized by annulospiral endings and located toward the center of the spindle, is sensitive to the rate of change of muscle length while the neural output of the secondary set, those with flower spray endings and located toward the ends of the spindle, appear to represent an instantaneous muscle length measurement. The second type of muscle receptor, the tendon receptor, appears to be a strain measurement mechanism for its neural output increases as does the strain on the muscle. The total neural response in muscle contraction is characterized during the onset phase by high spindle output and low but increasing tendon output. As the strain increases and muscle movement slows, the response is characterized by high tendon receptor output and low spindle output.

As G loading increases, it appears that muscle tone changes owing to the increase in inertial weight of the tissue supported by the skeletal frame. Some muscles may relax and elongate; others are probably forced into contraction in an attempt to minimize tissue deformation due to the G load. One cannot help noticing the potential lateral and longitudinal acceleration sensing mechanism formed by the inverted pendulum condition of the head, neck, and shoulders coupled with their muscular restraint structures and associated neural feedback.

With respect to the third category, information on the perception of flesh pressure indicates that the pressure gradient existing over a given section of flesh is perceived, rather than the absolute magnitude of flesh pressure. There appears reasonably consistant agreement that the prime pressure-sensitive cell is characterized by the Pacinian Corpuscle situated in a deep flesh location. These cells are onion-skin-like laminations surrounding a nerve fiber ending. Deformation of this cell due to environmental pressure causes nerve impulses in the sensory fiber.

As the inertial weight of the torso increases due to increased G loading, the pressure gradient over the buttocks changes as the primary bone structure in this region, the ischial tuberosities, transmit loading to the surface of the seat. The flesh trapped between the ischial tuberosities and the seat is subjected to increased pressure and the pressure-sensitive receptors in this area respond.

Muscle and pressure receptors are not necessarily confined to locations in the external regions of the body but are likely responsible for perception of visceral and vascular system acceleration effects as well. Here the receptors are located deep within the body as a part of, or adjacent to, the internal organs and circulatory system components.

The fourth category of acceleration-induced physiological change mentioned earlier is that of touch, or area of contact change. Under increased G loading the subject settles deeper into the seat, bringing a larger portion of his buttock and thigh flesh area into contact with the seat. A more informative way of stating this is that because of the acceleration environment more of the seat touched the subject's flesh; the subject did not actively seek to touch more of the seat. The receptor units of interest here are those allied with the sense of cutaneous touch. These include a number of different types of receptor units, such as hair cell detectors and pressure receptors; however, the pressure receptors here are those located near the surface of the flesh and affiliated with cutaneous deformation sensation as opposed to the deep-flesh pressure receptors affiliated with flesh pressure discrimination.

Taken individually, the elements of the haptic system respond with information concerning the movement of the body due to G loading in a rather segmented manner. It appears that no one element provides the spectrum of information necessary to define what is happening to the body. Fortunately, it seems that haptic system element outputs are employed in a covariant manner to provide a more sophisticated definition of body position and motion. Further, haptic system outputs, at a higher order of sensory system hierarchy, are merged in a covariant manner with vestibular and visual input to further refine this complex perception.

HAPTIC SYSTEM RESPONSE

Some very interesting work has recently been completed in the form of a thesis presented by Mr. D. R. Gum at the Ohio State University. the thesis, MODELING OF THE HUMAN FORCE AND MOTION SENSING MECHANISMS, documents the development of mathematical models of the head/muscle and body pressure sensing mechanisms and compares the response of these new models to that resulting from established mathematical models of the vestibular system's semicircular canals and otoliths. Forcing functions representative of the force profiles resulting from aircraft motion were employed as model drivers.

Although the head/muscle and body pressure models are initial representations (verification of one-to-one correspondence with the mechanisms they represent is pending comparison with more experimental data than that used in the generation of the models), the initial observations indicate a more rapid response available from the head/muscle and body pressure sensing mechanisms than that available, under identical forcing functions, from the semicircular canals and otolith. Although the body pressure sensing mechanism is subject to rapid adaptation with consequential stimulus decay, the minimal time delays between applied force and perceived pressure as well as the direct coupling between this mechanism and the aircraft cause it to be very valuable in kinesthetic determination.

Further, the thesis points out that muscle receptor output arising from muscle restraint of inertially induced head movement very closely matches the forcing function and does not seem to be subjected to adaptation, thereby making this neural response an excellent source of sustained kinesthetic stimuli.

MOTION SYSTEM LIMITATIONS

The major thrust of motion system technology has been aimed at providing the motion cues thought necessary or useful in the performance of specific tasks for learning or maintaining task proficiency. The spectrum of devices developed so far covers a long trail of ever-increasing sophistication, from simple two-degree-of-freedom devices capable of pitching and rolling, to large six-degree-of-freedom motion platforms with impressively large acceleration and excursion capabilities. In use, these devices are quite dramatic in increasing the realism of many learning tasks. In current flight simulators, inputs are being provided to many informational channels which are essential to the learning process.

A large portion of motion system development has rightfully centered around the investigation of the vestibular system. Until recently, little overt effort has been aimed directly at the haptic system channels. Apparently it was thought that if the vestibular sense could be adequately stimulated, proper inputs would simultaneously exist for the haptic system. To an extent this is sound reasoning; however, it fails to address a number of important questions.

For example, how important is haptic system stimuli in kinesthetic determination? Can such stimuli be generated in total or in part by means other than inducing inertial effects with a motion system? If only a portion of the haptic system spectrum can be so stimulated, would this relax some of the kinesthetic stimuli producing demands made upon motion systems or provide cue maintenance when operating beyond the capabilities of the motion system?

Motion systems, owing to their mechanical constraints, produce the most useful stimuli, or "cues", during the onset phase of low-level, short-term accelerations. However, as the accelerations become larger in magnitude and longer in duration, the capabilities of the motion system are approached and cue generation constrained or terminated. The impact of this problem is not precisely known. If the problem produces an impact on the learning process, it will be most noticeable under the conditions in which we expect kinesthetic perception and motion base limitations to be most prevalent. These conditions are encountered in learning to pilot high-performance aircraft, where accelerations are sustained over periods of time outside the capacity of conventional motion simulation systems.

The large, long-term acceleration environment, then, appears to offer the conditions under which a device designed strictly for haptic system excitation might produce the most useful data required in answering these questions. This device, which in concept has become known as a G seat, would be developed as a system, independent and separate in operation from the motion system but fully capable of being inserted into the motion system environment. The neural response from skeletal attitude changes, muscle tone changes, deep flesh pressure changes, and touch or area of contact changes would form the spectrim of stimuli of concern to which the design must be addressed. Evaluation of haptic system element stimulus importance would follow in those areas of the total spectrum in which the device appears to provide credible stimuli.

RESEARCH ENVIRONMENT

The evaluation of stimulus importance as it relates to the question of transfer of training is a complex task and certainly subject to a rigorous implementation of classical experimentation procedures. Ideally, control and experimental concepts should be clearly defined and structured in a manner which permits the experimenter assurance that performance differences are a direct consequence of experimental parameter variation and not due to extraneous changes.

Within the field of aircraft simulation the complexity arises, in part, from the broad complement of stimuli available to the subject and upon which discriminatory analysis may consciously or unconsciously be effected. Unless stimulus coupling is defined and known beforehand, the omission of large blocks of available stimuli such as that incurred in single task experimentation conducted outside the environment of the total complement of available stimuli prodices results which must be considered suspect when reinserted within the total complement of stimuli. Secondly, task loading forms a part of the control and must be considered as having a bearing on stimulus utilization until proven otherwise.

In the field of simulation these considerations indicate that in the interest of accuracy and applicability of findings, the evaluation of stimulus importance can best be accomplished with simulation systems providing state-of-the-art stimulus complement, task loading commensurate with the actual task, and above all, systems which are designed with the type of flexibility required to permit stimulus degradation, substitution, or selective omission.

Two systems which closely approximate these conditions are currently being developed at the Simulation Products Division of The Singer Company. The Air Force Simulator for Air-to-Air Combat (SAAC) Program will investigate, evaluate, and optimize training devices designed specifically to improve the combat proficiency of accomplished fighter pilots. A second Air Force program, the Advanced Simulation in Undergraduate Pilot Training (ASUPT) Program, will employ a research-oriented simulation system, capable of simulating T37B type aircraft, to pursue the optimization of training devices designed for a less experienced segment of the military pilot population - the undergraduate pilot. Both programs will employ similarly designed G-seats.

The Simulation Products Division prototype G-seat has been developed for the ASUPT program. The ASUPT simulation system includes dual cockpits, each equipped with a G-seat. The cockpits are each mounted on 60-inch stroke, six-degree-of-freedom motion bases with full wraparound, computer-generated visual displays. A Systems Engineering Laboratories Systems 86 computer forms the computational facility and nearly all programming is in Fortran IV floating point. The software programs are specifically designed to permit experimenter alteration of structure and content of the simulator subsystem software.

The fact that the prototype G-seat is to be evaluated within this type of research facility is considered extremely important in that the nature and importance of stimulus coupling existing between the haptic, vestibular and visual sensory systems is not known; consequentially, the research attributes of not only the G-seat system but also the motion, visual, and flight systems are considered fundamental to the primary G-seat tasks of evaluating the importance of haptic system sensory input and determining whether G-seat-induced haptic system stimuli can extend kinesthetic simulation beyond the capabilities of the motion system. The research design and mission of ASUPT forms a very desirable and necessary environment for this evaluation.

HARDWARE DESIGN

ORIGINS

The idea of employing a seat designed to induce body manipulation controlled according to the precepts of a drive philosophy so that acceleration sensations may be perceived is not new. A number of devices have been designed, ranging from simple single-bladder inflatable seat cushions to complex systems employing upholstered movable plates and retractable arm and leg straps. The success or failure of these devices remains somewhat shrouded in mystery, for little documentation has been found describing either the results achieved with these devices, or more importantly, the manner in which they were driven and the stimulus environment in which they were tested.

A casual survey of the field of aircraft simulators produced in the last decade reveals that few if any of these simulators contain seats designed to stimulate the haptic sensory system. It might be assumed that this represents an indictment of G-seat utilization; however, the author reasons that a valid finding against G-seat utilization would be the product of testing within a total simulation environment, preferably a research facility, and as such, the findings would likely be documented and known within the field of simulation equipment users and producers.

Since this does not appear to be the case, Simulation Products Division, under the ASUPT program, has proceeded on the basis of the assumption that research pertaining to G-seat-stimulated haptic system resonse is lacking, and that to properly address the problem the system designed must be a research tool in itself and fully compatible with the broader research endeavor of the ASUPT facility.

BASIC CONCEPT

Set forth in the section entitled "Preliminaries" is a survey of the investigation of the haptic system conducted prior to hardware development which identifies the sensory system channels of interest. Four firm guidelines emerged:

1) Skeletal attitude changes, muscle tone changes, flesh pressure changes, and area-of-contact changes all result from movement of the body.

2) It is desirable to directly drive these changes so as to minimize or eliminate the dependance upon inertially produced movement; consequently, we must "get hold of" the subject's body.

3) The task environment of our subject, that of piloting an aircraft, dictates the position of the subject; he is seated and the drive device must be designed for this position.

4) A part of the haptic system stimulation is produced because of the subject's coupling to, and interaction with, the seat.

The most straightforward, realistic route to approach the subject's body is through the object with which he is most often in contact — his seat, lap belt, and shoulder harness.

Recognizing that the subject's own weight can be passively made to complement the activity of a movable seat, the author reasoned that seat-induced bodily movement could be made to serve skeletal attitude changes, flesh pressure changes, and area-of-contact changes quite well. Muscle tone changes would be available wherever seat support or skeletal attitude shifts could be either subliminally altered, or altered behind the mask of seat movement for complementary purposes, so as to cause gravity forces to change muscle loading. Whereas the inverted pendulum effect might be successfully approached in this manner, the feeling of increased weight of the arms and shoulders probably could not be achieved without the aid of some device which could, without radically altering the pressure gradients in the arm and shoulder flesh, apply force.

Viseral and vascular system changes appeared, in general, to fall outside the realm of G-seat capability. It is possible, of course, that some visceral stimuli would be available as a byproduct of providing an active lap belt for flesh pressure stimulus production.

The author has not arbitrarily ruled out more esoteric means of driving the subject's body; these simply will be held in abeyance pending information concerning their feasibility of implementation and possible adverse effects on the subject's health. In the interim, the movable seat concept capitalizes on the presence of seat coupling in the normal task, the fact that approaching the subject through the seat presents few problems concerning the subject's well being, and the fact that a reasonable portion of the haptic system stimuli of interest can be addressed with seat movement.

ADDITIONAL GUIDELINES

To aid in arriving at an initial seat configuration a number of design guidelines were considered. The more important were:

1) Visual and Aural Fidelity - The seat must appear to be an ordinary T-37B-type seat. Any other configuration providing an ongoing visual or aural reminder of the presence of a G-seat may compromise the seat's usefulness. This ruled out the implementation of any unusual straps or harnesses to control the movement of head, arms, and lower legs. However, movement of the main portion of the torso and upper legs could be controlled by movable seat cushion surfaces. This movement would also induce skeletal attitude changes of limbs resting on the rudder pedals and stick. Further, movable seat cushions constructed of pneumatically driven air bladders could produce surface flesh pressure variations and induce a feeling of hardness or softness.

2) Flexibility - In that the optimum way to drive the seat is to be a product of experimentation, it was necessary to adopt a seat cushion design which produced the least number of constraints in achieving various planar attitudes, elevation, and form. Seat pan and backrest cushions composed of mosaics of individually controlled air cells was selected as an extremely versatile approach.

3) Safety - The seat must not produce a safety hazard to those using the seat. The movable cushions would be fully upholstered and excursion limited, and taken by themselves present no safety hazard. An active lap belt or any other device which could, in effect, squeeze the subject would be designed with automatic release mechanisms which would safeguard the subject from excessive force.

INITIAL CONFIGURATION

The initial configuration of the G-seat is depicted in Figure 1. The basic elements of the seat, mounted in a standard T37B aircraft seat frame, are:

1) Seat Pan Cushion - A 16-inch by 16-inch cushion is formed by a mosaic of sixteen square plastic air cells.

2) Backrest Cushion - A 16-inch by 23-inch cushion is formed by a mosaic of nine rectangular plastic air cells.

3) Thigh Cushions - Adjacent to the seat pan cushion on either side is a row of three air cells which stand slightly higher than the neighboring seat pan cushion cells, thus causing the seat to be somewhat bucket-shaped. The inclusion of thigh cells was based on a hypothesis that stimulation of the fleshy area on the outside of the thighs could enhance the sensation of lateral translational and roll accelerations, as well as increase flexibility in driving flesh pressure and area-of-contact changes.

4) Lap Belt - The lap belt is driven in extension and contraction. The seat is equipped with a standard shoulder harness. Although this device is not actively driven, there is some coupling of the lap belt drive into the shoulder harness because the lap belt buckle also serves as a terminus for the shoulder straps.

5) Upholstery - The seat pan, backrest, and thigh cushions are overlaid with a 0.5 inch-thick layer of closed cell foam padding. The seat is upholstered in canvas duck with side panels of elasticized material to permit cushion movement. Cushion zippers permit entry to the internal air cells.

The drivable elements of the seat, therefore, are 31 air cells and a lap belt actuator. Each of the 32 items is individually controlled via pneumatic hoses leading from the pneumatic control package to the seat. The pneumatic control package governs device activity solely through pressure control of a noncritical mass of air. The 32 pneumatic control devices are in turn governed in open-loop fashion by computer linkage operating under the control of the G-seat software. A block diagram illustrating the G-seat system appears in Figure 2.

DESIGN EVOLUTION

Early in the development phase, a breadboard test article was constructed to evaluate the suitability of the initial configuration. Although breadboarding was limited to seat pan and thigh cell testing (conducted separately) serious conceptual flaws were revealed. Paramount was the observation that conflicting stimuli were being produced by the plastic air cells. In attempting to settle the seat and produce skeletal attitude changes commensurate with large headwards accelerations, the surface of the cushion, due to the lower pneumatic pressure, became more pliable and conformed more closely to the shape of the buttocks, thereby reducing buttock flesh pressure gradients which, ideally, should be amplified under this acceleration

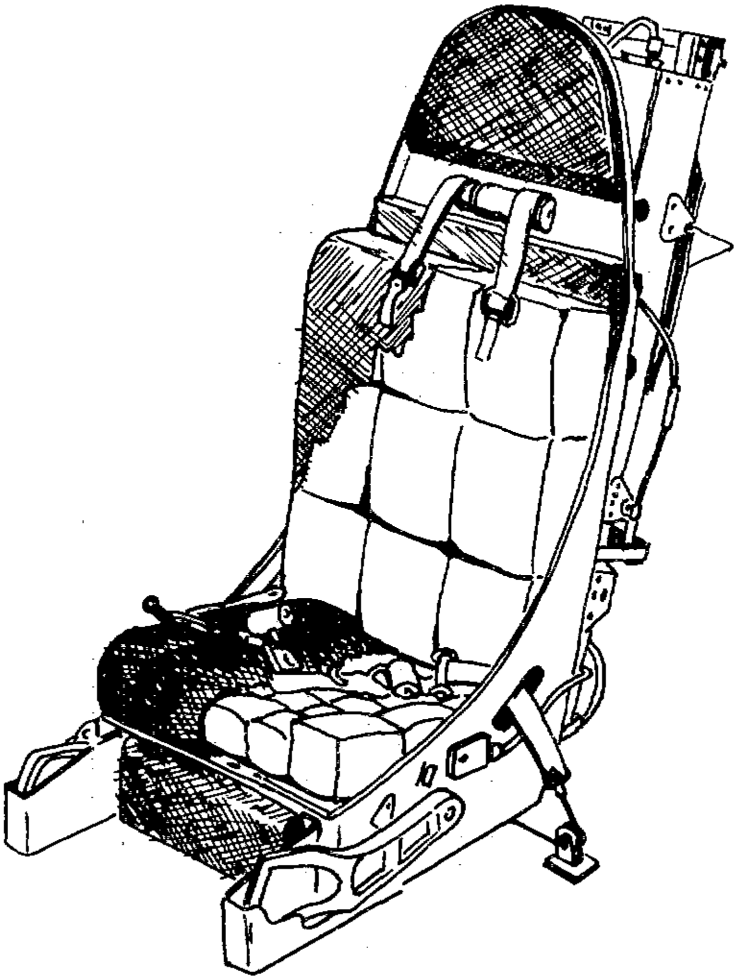


Figure 1 PERSPECTIVE VIEW OF G-SEAT

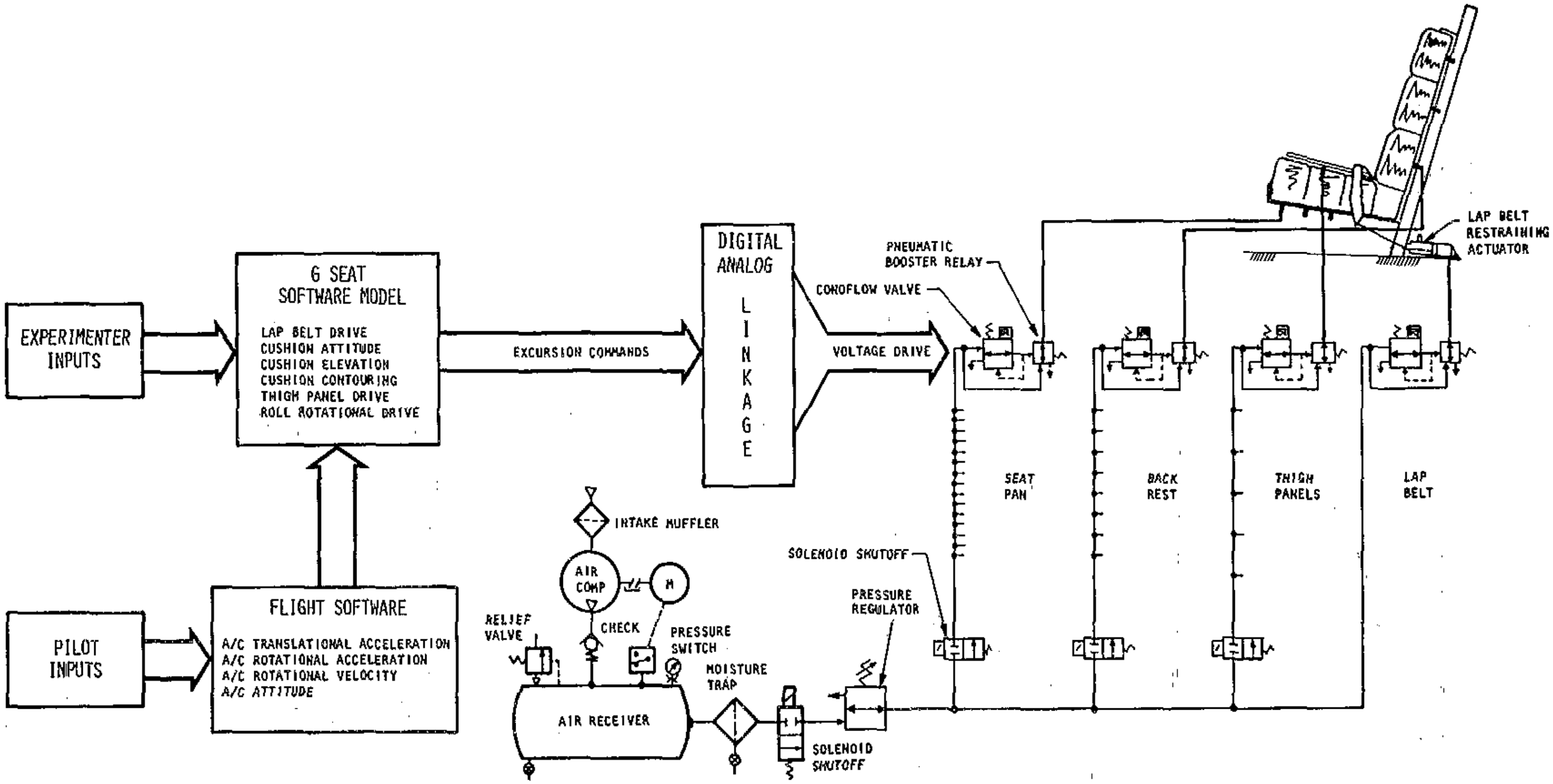


Figure 2 G-SEAT SYSTEM BLOCK DIAGRAM

condition. Equally as undesirable was the very turgid surface existing under footwards acceleration conditions.

Secondly, the seat had a tendency to "balloon" by varying amounts, depending on the physical characteristics of the subject occupying the seat. This feeling seemed aggravated by subject movement on the seat. As the subject shifted his weight about, the air cells would seek a new equilibrium point compatible with the new load. Allied with this was the uncanny feeling of thigh cells which, within the bounds of their excursion capabilities, tended to follow the subject's thigh during leg movement.

A third very real concern was the understanding that the research capability of the seat could be seriously compromised if it were not possible to provide the experimenter with a seat which reacted in a more predictable manner and less capriciously to subject movement within the seat and subject weight and shape variations. The latter problem is dramatically illustrated in Figure 3 which represents thigh area loading data taken by the author on subjects from pilot and nonpilot populations.

The results of the breadboard testing demanded reconsideration of the basic element of the seat: the air cells employed in the seat pan, backrest and thigh cells. That effort, as well as the lap belt design, which was not materially affected by breadboard results, is presented within this section. Also included is a description of the pneumatic control package employed in the G-seat system. Figure 4 is a picture of the G-seat after redesign.

SEAT PAN AND BACKREST AIR CELL REDESIGN

To counter the problem of the generation of conflicting skeletal attitude and flesh pressure sensations, it was decided to isolate the flesh from contact with the pliable top surface of the air cell by employing an air cell top plate. Thus, the air cell becomes strictly an excursion device similar to a ram, but permitting the top plate the two degrees of rotational freedom necessary to form a near-continuous seat surface.

Flesh pressure gradient changes may be achieved by controlling the elevation of a cell with respect to the elevation of neighboring cells. The mosaic form of the seat pan and backrest, and in particular the large number of mosaic elements and consequential small surface area of each element, make this "contouring" approach feasible. Although contouring places an additional burden on the G-seat drive signal software, the ability to decouple and individually drive flesh pressure gradients and skeletal attitude changes is attractive in a research system.

Cushion "ballooning" and the problems associated with seat-induced movement due to subject movement as experienced in the breadboard tests were attributed to the open-loop nature of the pneumatic control system and the fact that within the confines of air cell excursion the cell is restrained solely by the weight of the subject's flesh. To counter this problem, tensile springs were incorporated within the bellows design. The spring rate adds to the air cell load due to the subject and, depending on the spring rate selected, produces a stiffer seat (less prone to movement induced by the subject). Of equal importance, the effect, in terms of cushion shape variation of subject load distribution variation is reduced, thereby providing the experimenter with a more predictable system. The penalty, of course,

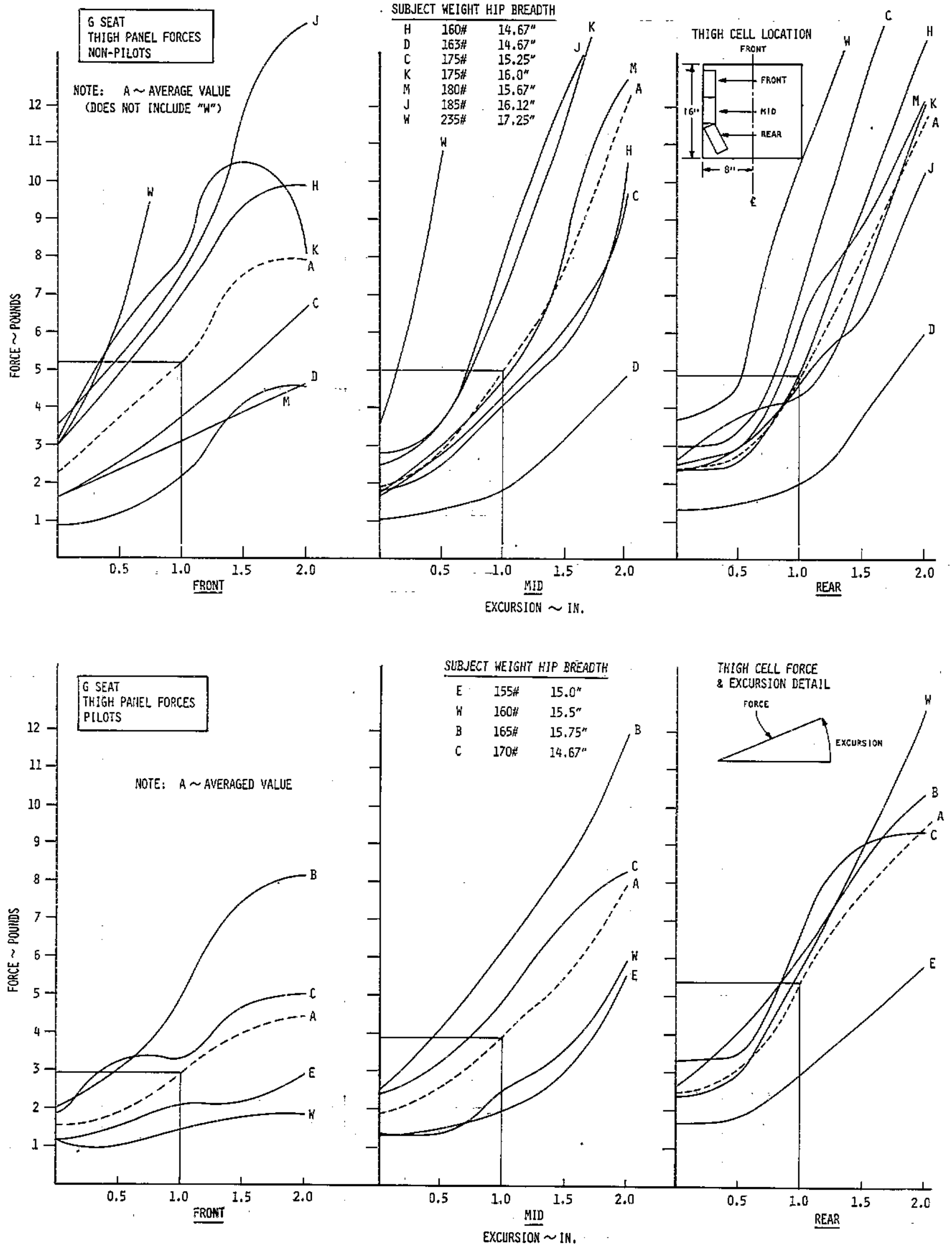


Figure 3 THIGH AREA LOADING DATA

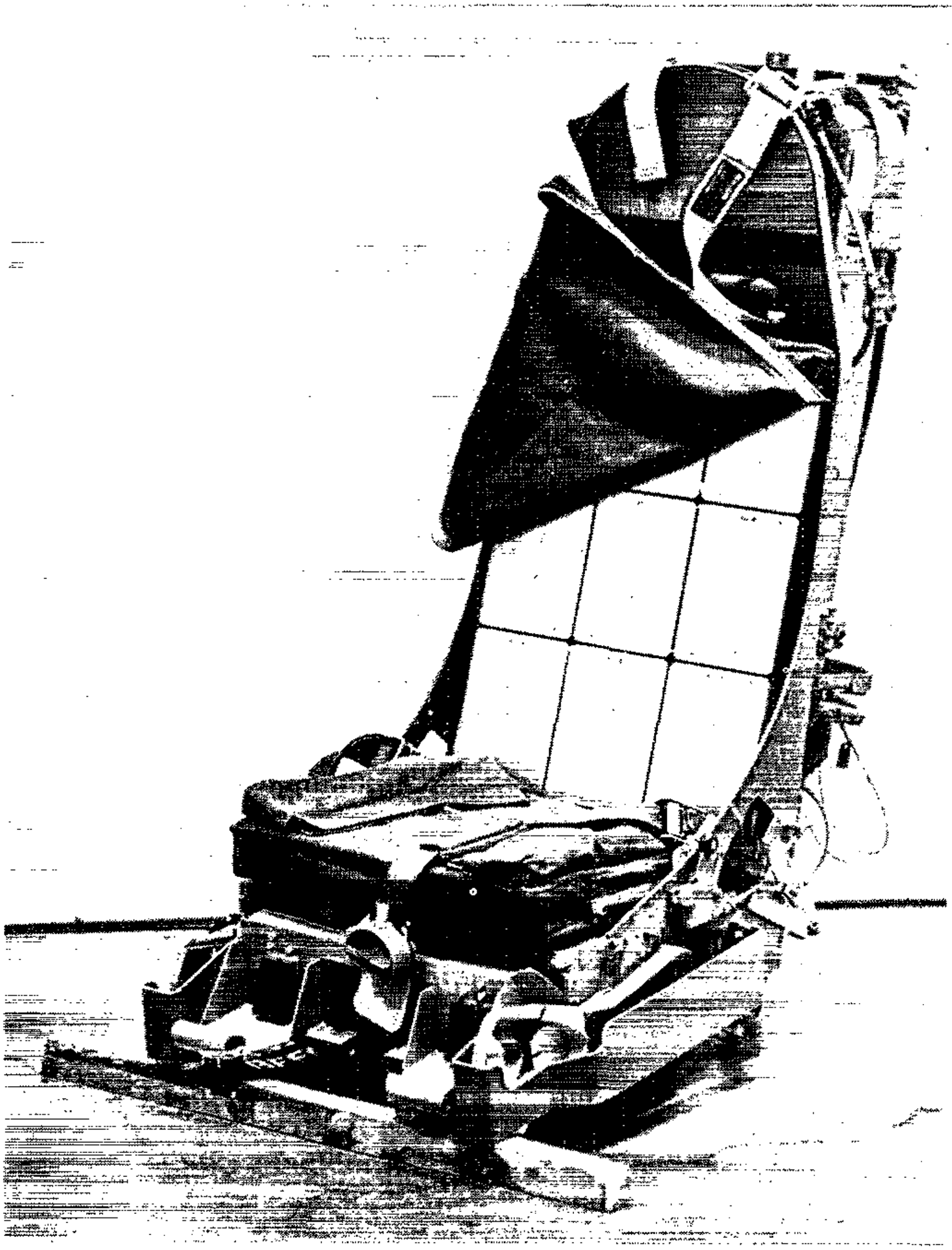


Figure 4   G-SEAT IN FINAL CONFIGURATION

is a requirement to operate at higher pneumatic pressures.

The addition of the contouring concept and the need to define a suitable spring rate required, at minimum, a more refined estimate of cell loading anticipated under average subject conditions. The author has found very little anthropometric data pertaining to buttock and back load distribution. In the case of the thigh cells, the data presented in Figure 3 is the product of a simple test device constructed by the author. Figure 5 depicts the estimate of buttock and back loads of a 160 pound "average" subject in the seated position. This approximation was derived from data taken by Lay and Fisher on the Universal Test Seat and converted to equivalent loading for the mosaic form of the G seat. It is interesting to note that aside from its primary role of investigating haptic system importance, the G seat could also be used to refine buttock and back load distribution data.

Seat pan and backrest cell excursions of $\pm$1.375 inches and $\pm$0.875 inches, respectively, measured from a neutral midpoint condition, were considered sufficient to provide experimenter flexibility in cushion elevation, attitude, and shape variations. Based on these stroke requirements and the estimated load distribution of Figure 5, plus an analysis of anticipated load variation resulting from subject rudder pedal and stick activity, as well as motion-base-induced attitude changes, tensile spring rate ranges of 10-20 pounds per inch for seat pan cells and 50-100 pounds per inch for the larger backrest cells appeared desirable. Dimensional constraints, however, would force selection from the low end of these ranges.

The inclusion of an internal spring acting in tension within the plastic bellows, the associated complexity of assembly, and the higher pneumatic pressures and resultant cell buckling caused the plastic air cell implementation within the seat pan and backrest to be abandoned in favor of the metal bellows pictured in Figure 6. The dimensions of the cushion mosaic elements were maintained at their initial design values and, in order to accommodate the rectangular mosaic element of the backrest with cylindrical air bellows, two metal air bellows are included within each backrest mosaic and tandemly driven.

The design and construction of the metal bellows permits, via heat treating processes, the incorporation of a tensile spring rate during fabrication, thereby reducing the task of final assembly to that of securing the top and bottom plates. The performance of the metal bellows in terms of linearity and low hysteresis is is extremely good, as evidenced by the test plot of Figure 7. Good linearity of both the bellows and pneumatic control device is fundamental to open-loop operation of the control system as well as simplifying the associated software.

THIGH AIR CELLS

The original concept of employing two banks of air cells of slightly higher elevation than the seat pan air cells and located to the outside of the seat pan cells was abandoned in favor of using two thigh panels, each composed of three plastic air cells fabricated in such a way that their excursion strikes an arc. These cells are housed in single file in an upholstered container which rides on top of the seat pan. Velcro strips

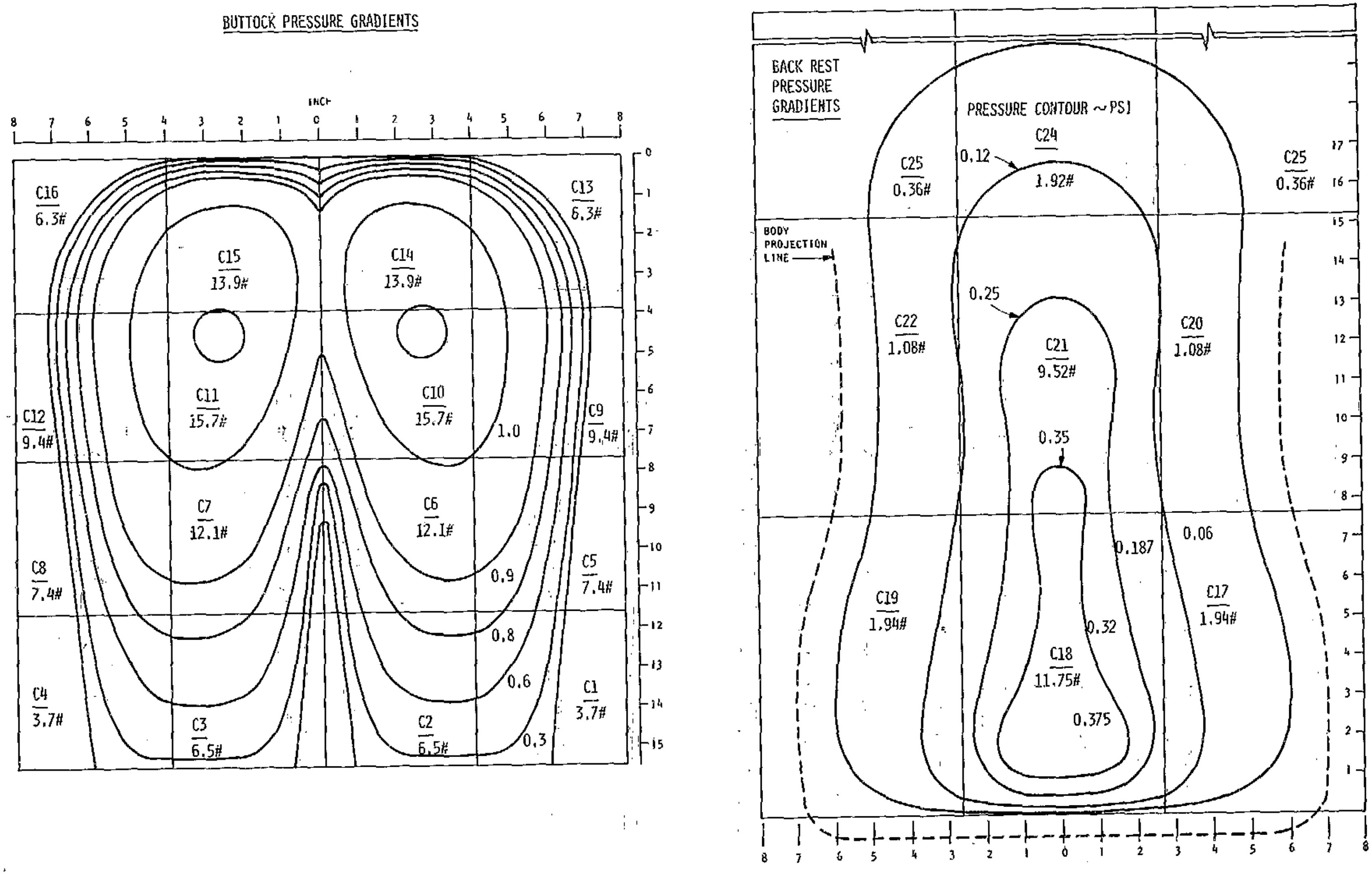
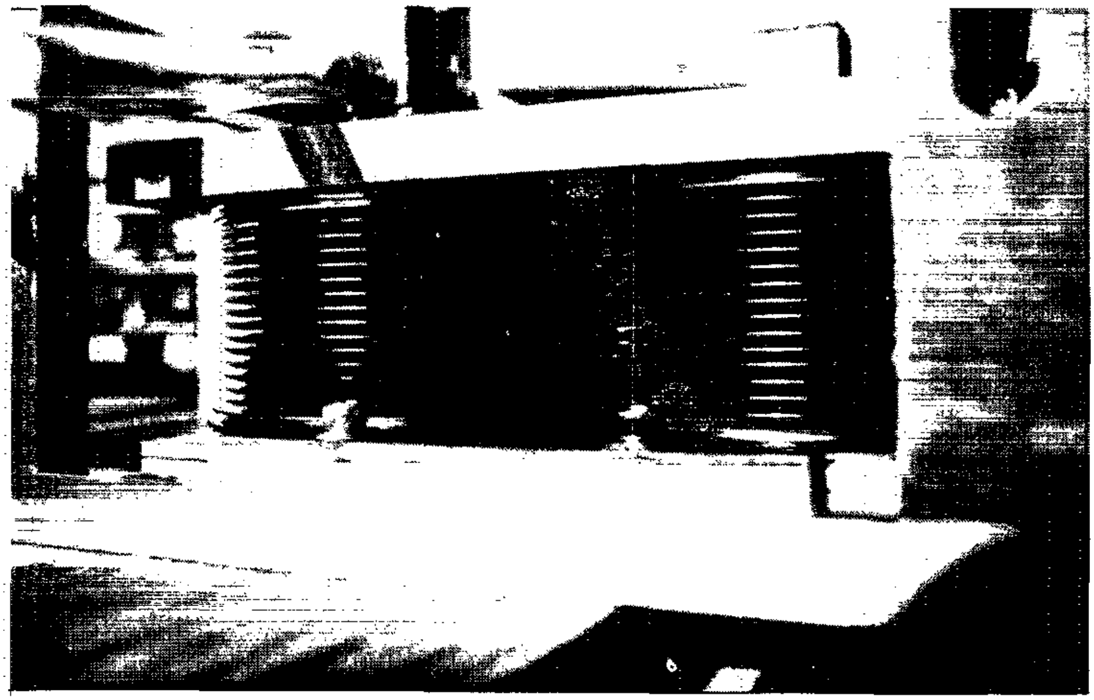
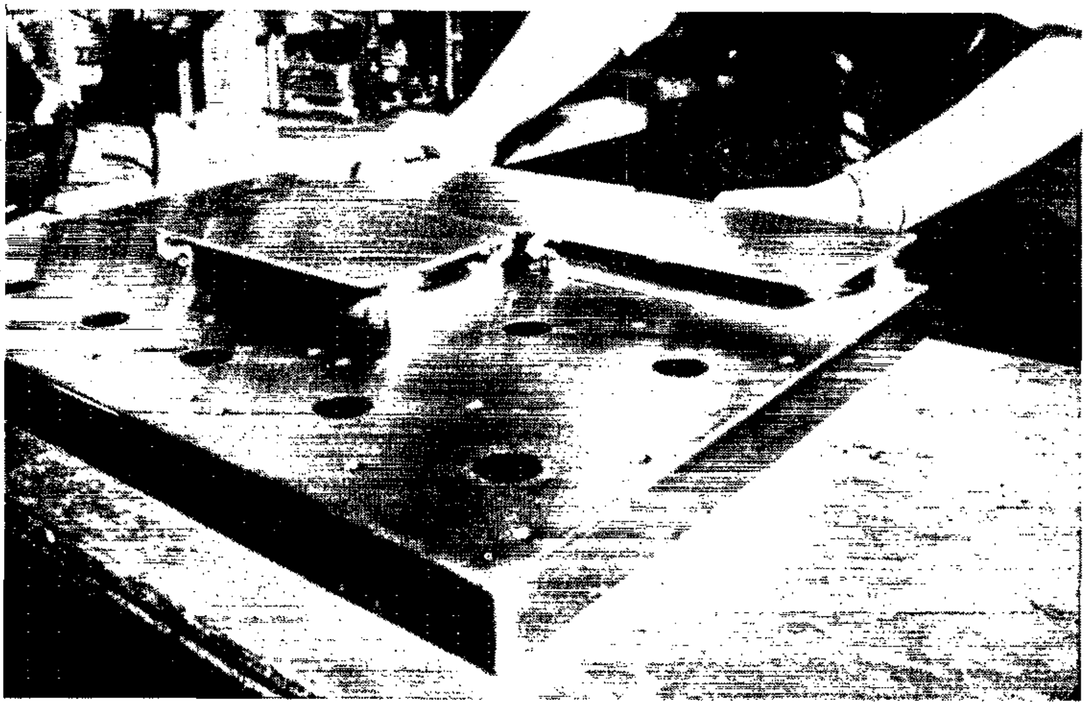


Figure 5 ESTIMATED BUTTOCK AND BACK LOAD DISTRIBUTION

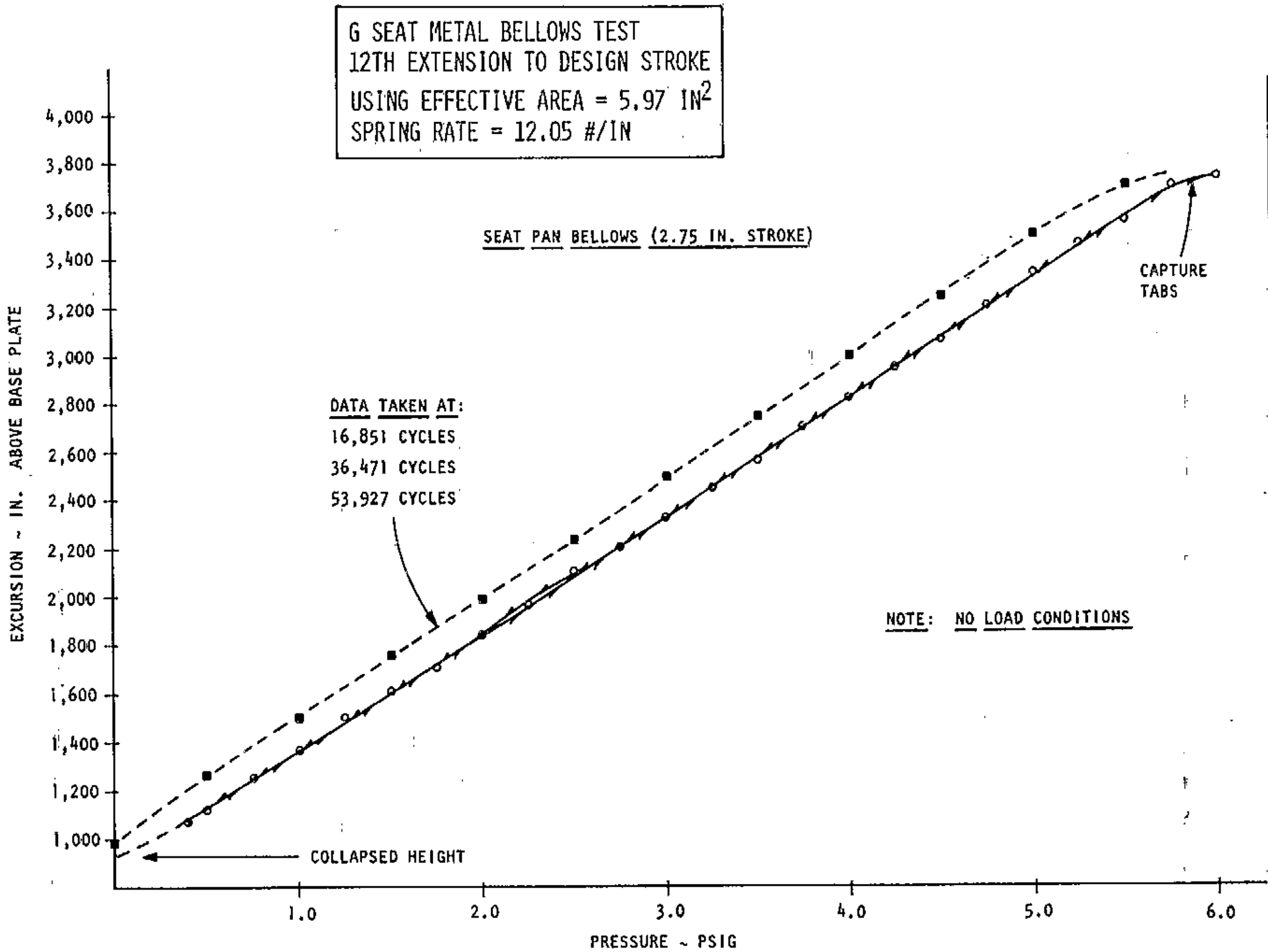


BACKREST CELL INVERTED IN TEST RIG - NOTE
TANDEMLY DRIVEN BELLOWS



BACKREST CUSHION IN ASSEMBLY SHOWING BELLOWS
PLACEMENT IN MOSAIC FORM

Figure 6 METAL BELLOWS



PRESS	UP	DOWN	UP	DOWN
	.4/			.3/
	1.078			1.046
0.50	1.125			1.125
0.75	1.250			1.250
1.00	1.375			1.375
1.25	1.500			1.500
1.50	1.609			1.609
1.75	1.703			1.743
2.00	1.843	1.843		1.843
2.25	1.968	2.000	1.984	1.984
2.50	2.109	2.093	2.109	2.109
2.75	2.203	2.203	2.203	2.203
3.00	2.328	2.328	2.328	
3.25	2.453	2.453		
3.50	2.562	2.578		
3.75	2.703	2.703		
4.00	2.828	2.828		
4.25	2.953	2.953		
4.50	3.078	3.078		
4.75	3.203	3.203		
5.00	3.343	3.343		
5.25	3.468	3.484		
5.50	3.578	3.578		
5.75	3.703	3.718		
6.00	3.750			

Figure 7 METAL BELLOWS EXCURSION VS. PRESSURE PLOT

on the seat pan upholstery as well as the underside of the thigh panels permit the thigh panels to be located at variable distances from the XZ plane of symmetry of the seat, or, if desired, removed entirely from the seat. This approach provides the experimenter with an added degree of flexibility not included in the initial configuration.

The plastic thigh panel cells are trapped within a hinged, spring-loaded, clamshell-like device designed so that pressurization of the cell causes the top surface of the device to travel an arc-shape path against the thigh. This design embodies the same changes incorporated within the seat pan and backrest air cells: a solid top plate to isolate the flesh from the pliable surface of the cell, and in this case, a torsion spring rate. Figure 8 pictures two thigh panels with one cell removed and opened beyond the midpoint position. Note that the cell top plate is split to provide less discontinuity in fitting against the thigh.

LAP BELT

Haptic system stimuli are obviously not limited to the thigh-buttock-back area of the human body, but originate from the ventral area as well. It is suspected that lap belt pressure distribution, particularly over the anterior ilial protrusions, is a significant stimulus for the evaluation of acceleration and/or orientation conditions of the type which tend to cause the subject to lift in his seat. The lap belt drive, capable of lap belt extension and contraction from both sides of the seat about some "snug buckle-up" state, is used to provide ventral area pressure distribution stimulus. Contraction and expansion of this nature may also provide, as a byproduct, compatible visceral haptic system stimuli.

As pictured in Figure 9, housed under the seat pan is an actuator which is pneumatically controlled in much the same manner as the previously discussed air cells. The actuator is spring loaded so that pressurization to approximately 4.5 psi centers the actuator ram near the midtravel point. The actuator is connected to both ends of the lap belt by a shear pin equipped balance or pivot beam and flexible cable located within rigid guide tubing. Shear pin failure due to excessive belt loads disconnects the actuator from the belt. When the subject is buckled up, the buckle-up force acts to more closely center the lap belt actuator stroke.

Increased actuator pressures retract the lap belt from both sides of the seat up to a maximum of approximately 1.5 inches. Likewise, decreased pressurization relaxes the belt up to an equivalent amount. Data taken by the author on a number of test subjects of varying weights and physical sizes reflect that 120 pounds per inch is a reasonable approximation of the compressibility of the ventral area contacted by a standard width T-37B lap belt. There is, however, a fairly wide dispersion of data depending on the physical shape of the subject's lower torso, and although maximum lap belt forces of only 100 pounds are scheduled, the belt actuator mechanism is designed with added excursion capability in order to approximate these forces in subjects displaying greater compressibility, and secondly, to accommodate belt movement stemming from seat pan and backrest cushion-induced subject movement.

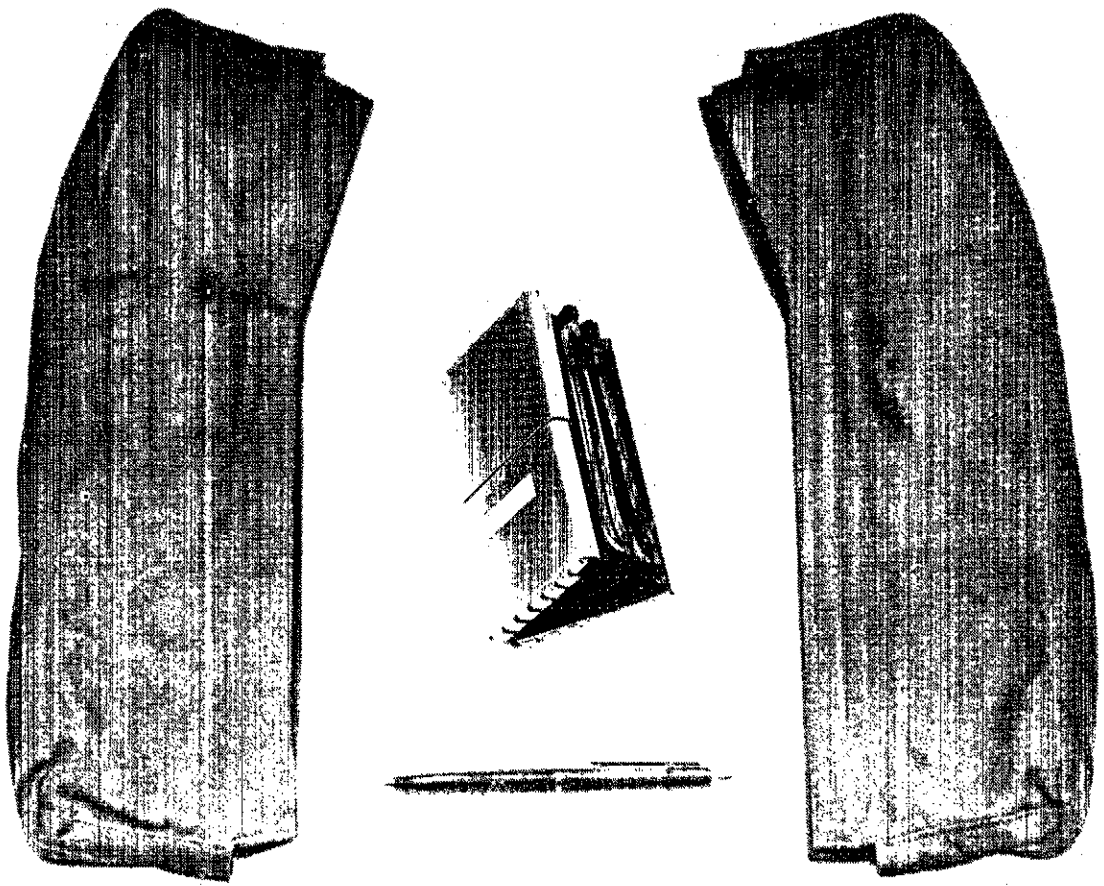


Figure 8 THIGH PANELS

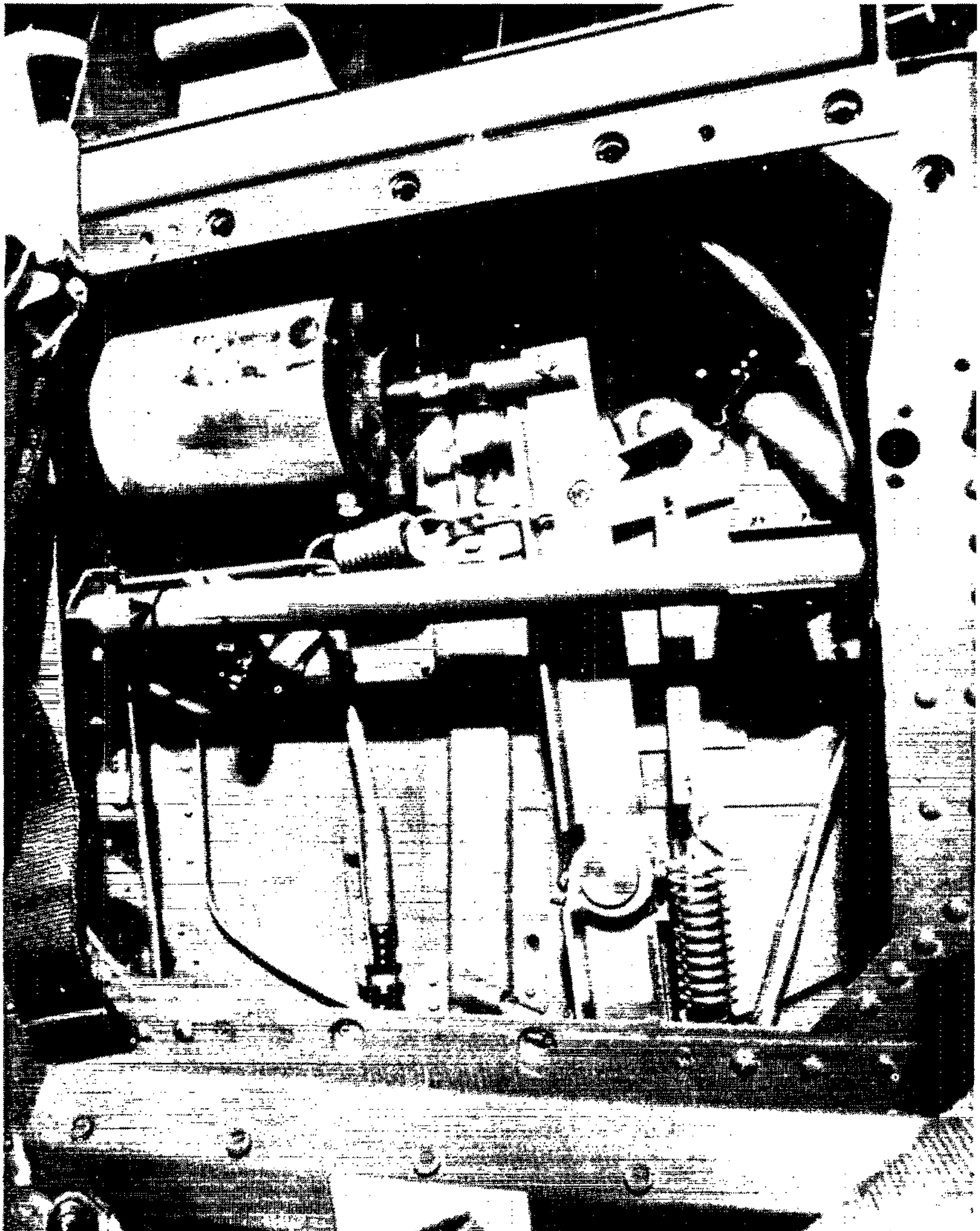


Figure 9   CAP BELT ACTIVATOR MECHANISM

PNEUMATIC CONTROL SYSTEM

As mentioned earlier, the lap belt actuator, the six thigh panel air cells, nine backrest air cells, and sixteen seat pan air cells are all treated as excursion devices. The amount of excursion is controlled by the pressure of air delivered to the device, the load provided by the spring rate of the device, and the body load supported by the device. Although the reader can probably mentally design a number of devices which might be fabricated to control the air pressure of each excursion device, it must be borne in mind that individual pressure control of the 32 devices is required, and cost thus becomes a critical factor. The method selected and described herein represents an economical approach to the problem of providing smooth pressure changes to each device.

Thirty-two low-pressure electro-pneumatic transducers packaged in banks of sixteen form the heart of the pneumatic control package. One such bank is pictured in Figure 10. Compressed air regulated at 25 psi is supplied to each of the 32 transducers. The pressure of the air output by each transducer varies linearly with the current of the control signal applied to the transducer, as illustrated in Figure 11. The control signal is made available through digital/analog linkages interfacing the control package with the computer software responsible for G-seat control.

Four of the more attractive aspects of the electro-pneumatic transducers are low cost, good linearity of output pressure versus input signal, good repeatability, and favorable impedance, permitting interfacing directly with the D/A linkage without the use of auxiliary buffer amplifiers.

It is anticipated that the majority of G-seat movement subject to kinesthetic discrimination will be low-frequency movement. Figure 11 demonstrates reasonable smoothness and continuity of pressure output versus drive signal input. The transducer will pass 4 cycles per second but with severe amplitude degradation. Frequencies of this range can be better supplied by other devices such as seat vibrators.

Two racks containing the transducers are situated on the floor beneath the cockpit's motion platform. The seat assembly and the transducers are connected by a 32-tube air supply bundle cut long enough and arranged in a "fall" so that full motion platform excursion is permitted without jeopardizing G-seat pneumatic control equipment. Tests were conducted to demonstrate that as long as the supply lines are not pinched motion of the bundle is not reflected in unwanted air cell excursion.

To ensure rapid exhaust cycle time, particularly in view of the long pneumatic lines connecting the seat and control assembly, each transducer is equipped with a one-to-one pneumatic booster relay. The exhaust capability of the booster is considerably higher than that of the transducer and the presence of the relay between air cell and transducer tends to dampen pressure oscillations.

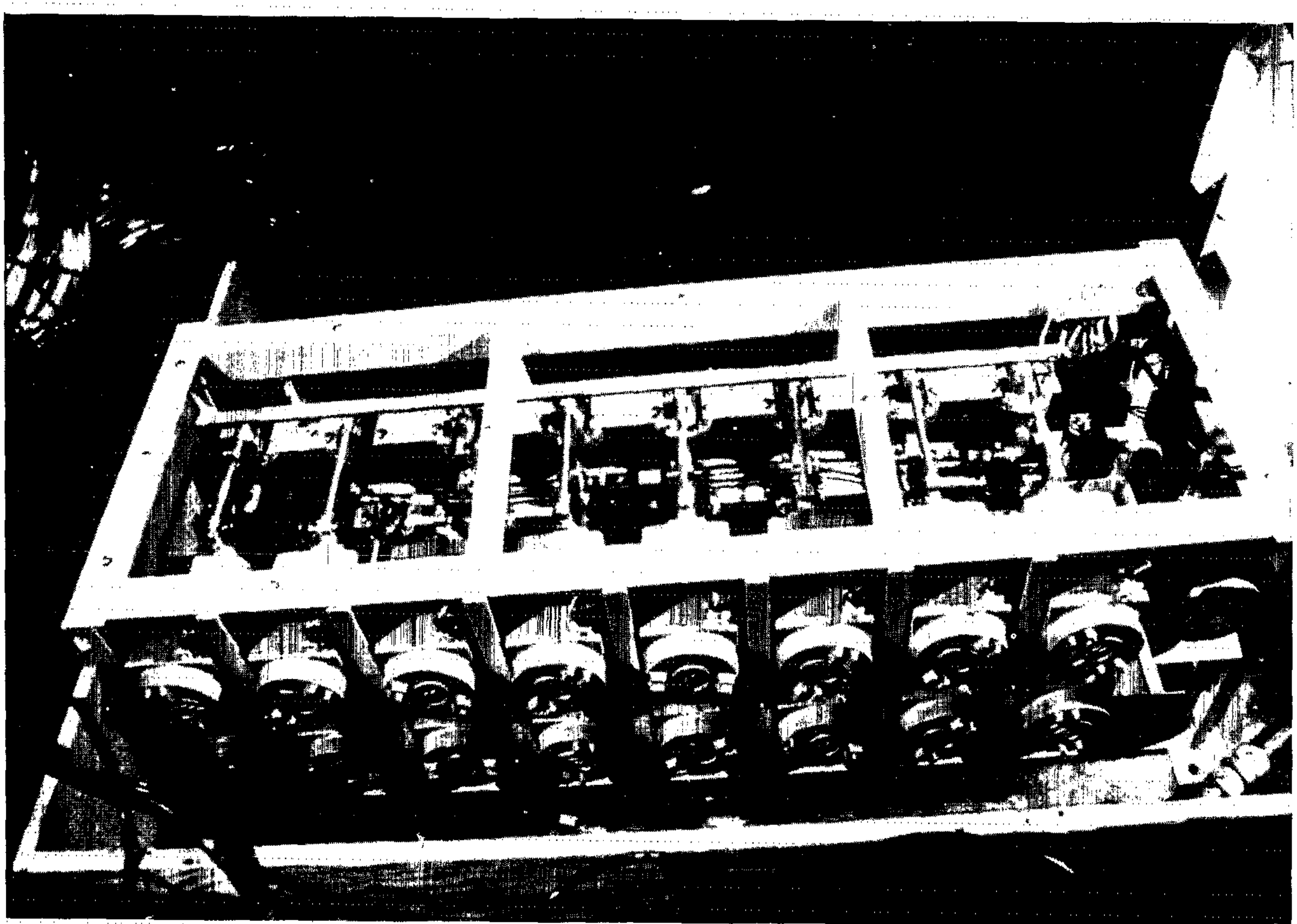


Figure 10 PNEUMATIC CONTROL DEVICE ASSEMBLY

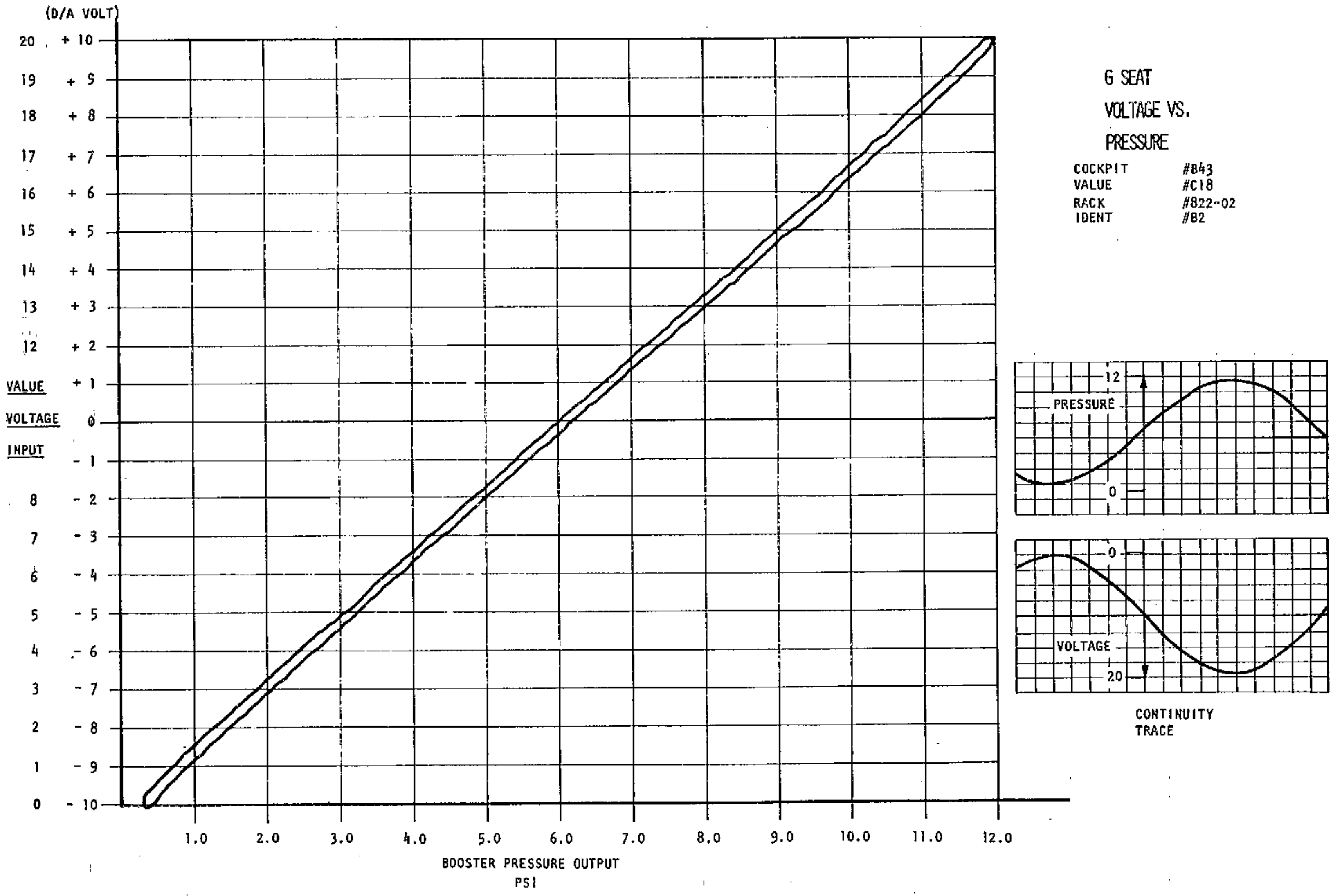


Figure 11 PNEUMATIC CONTROL DEVICE PRESSURE VS. DRIVE SIGNAL PLOT

SOFTWARE DESIGN

The software to drive the G-seat in response to simulated aircraft accelerations was developed in parallel with the hardware described in the preceding sections. Hardware changes which affected the software drive model were incorporated concurrently; this section describes the resultant model.

Although a number of preconceived notions existed concerning drive schemes which "ought to feel proper", it was necessary to recognize and admit that the "proper" or "best" way to drive the seat would be hypothesis until proven through research employing the G-seat system. Therefore a basic software development objective was to produce an extremely general purpose, flexible module, the structure and characteristics of which can, while remaining in the real-time mode, be altered by the experimenter. The basic software capabilities are described within this section and the initial drive philosophy introduced. Before commencing, a few basics should be mentioned.

BASICS

The axis system used by the G-seat software as a reference frame is constructed parallel to the aircraft body axis system; however, the origin is transferred to the pilot station and located at the approximate position of the pilot's torso. The + X axis is directed forward, generally along the thrust vector, the + Z axis is directed footwards, generally along the gravity vector when the aircraft is standing on the runway, and the + Y axis completes the right triad.

The simulated aircraft accelerations employed by the G-seat software are flight translational and rotational accelerations transferred from the aircraft center of gravity to the pilot station axis, wherein aircraft rotational acceleration materializes as an induced translational acceleration and is vectorially added to the pure translational acceleration components. Although these three translational acceleration components form the primary input to the G-seat model, exception is made for aircraft roll acceleration. Because of the small moment arm between the pilot station origin and the aircraft roll axis, a separate section of the G-seat software accepts and displays roll effects directly, rather than depending upon roll effects materializing as useful induced translation.

A fundamental premise in formulating the G-seat software is the concept that <u>aircraft acceleration equals seat position</u>. The seat is composed of excursion devices, and this concept simply implies that seat excursion is a scaled version of the magnitude of the current aircraft acceleration, with maximum seat excursion reserved for some preset maximum anticipated aircraft acceleration. In the normal 1 G state, the seat is maintained at a neutral point which is formed when the air cells and lap belt are near the midpoints of their respective excursion ranges.

In setting the control parameters establishing the initial drive configuration, or that mode of seat response in which G-seat-induced haptic system stimuli evaluation will commence, an initial assumption was made that, in general, the seat should "fall away" from the areas of increased flesh pressure normally resulting from seat/subject acceleration. An exception to this rule, of course, is the contouring concept wherein localized areas of the back and buttocks are subjected to increased flesh pressure. Although the two concepts sound contradictory, the mosaic form of the seat permits the seat to fall away from general areas of increased flesh pressure, yet within that same area, locally increase flesh pressure by altering the shape of the seat.

DRIVE CONCEPTS

The software drive concepts will be introduced in the context of the initial drive configuration; each concept can be readily altered to obtain a totally different drive.

SEAT TRANSLATION

The elevation of a complete set of cells, either or both the seat pan set or the backrest set, is caused to translate in unison a uniform distance. In the case of the seat pan, the translation abides by the activity of the Z axis acceleration component. Positive (footwards) acceleration produces increased seat pan air cell elevation and negative (headwards) acceleration produces a decrease in seat pan elevation. The backrest cells are similiarily sensitive in a like manner to X axis accelerations, with an opposite sign/excursion relationship to that indicated immediately above.

SEAT PLANE ORIENTATION

The plane formed by a complete set of cells, either or both the seat pan set or backrest set, is caused to be reoriented. The key to the reorientation is the seat pan plane which is driven, within the bounds of cell excursion, so that it approximates an orientation normal to the total acceleration vector, including the gravitational component. Remembering that one of the underlying concepts of the G-seat drive is that of scaling maximum excursion to maximum anticipated acceleration, it should be noted that the seat pan plane will not, in practice, be normal to the actual total acceleration vector, but rather to a scaled version thereof. This provides plane reorientation in the correct direction but at reduced magnitudes.

The plane of the backrest is driven in a similar manner to that of the seat pan, except that the sign convention is reversed along the X axis. That is, when the seat pan plane is pitched up, the corresponding backrest plane maneuver is pitch down, or top forward and bottom rearward. Seat pan plane and backrest plane sign convention for the Y axis is consistent; for example, seat pan roll left is accompanied by backrest roll left.

CONTOURING

Either or both the seat pan and backrest may be caused to assume a contoured shape which produces a flesh pressure redistribution thought to be compatible with body response to acceleration along any one or combination of axes. Six basic contours are considered; each pertains uniquely to either a positive or negative acceleration along one of the seat axes. The degree of contouring is governed by the magnitude of the acceleration component. Contour mixtures are realized in multicomponent acceleration profiles.

THIGH PANEL DRIVE

Thigh cell excursion responds to any or all of the lateral, longitudinal, and vertical acceleration components. The individual thigh cells respond uniformly to lateral acceleration. Rightward seat acceleration causes the right thigh panel to increase in elevation and the left thigh panel to decrease a commensurate amount. The reverse is true of leftward seat acceleration.

Secondly, the longitudinal consideration causes thigh panel response to X axis acceleration components. In this case the concept of a splay angle is introduced. Since excursion of the thigh cells is pie-shaped, fully inflating the forward air cell, partially inflating the middle cell, and exhausting the rear cell causes the surface of the thigh panel to be skewed by an angle referred to herein as a splay angle. The thigh panels are driven so that response to -X acceleration components yields splaying apart of the forward sections of the thigh panels. Similarly, the response to +X acceleration components is a splaying apart of the rear sections of the thigh panels. The severity of the splay angle is governed by the magnitude of the acceleration vector.

Vertical acceleration response of the thigh panels is a simultaneous uniform increase or decrease in the arc struck by each of the thigh panel cells. This is quite similar, in concept, to the seat pan translational concept, except that the excursion direction is reversed. For example, when the seat pan is caused to settle under headwards aircraft acceleration conditions, the arc struck by the thigh panels is caused to increase, bringing more of the seat into flesh contact and enhancing the feeling of "settling into the seat".

ROLL CONSIDERATION

As mentioned earlier, special provision is made to display roll effects. Under this concept it is possible to bias the excursion drive of the thigh panels and/or the outboard bank of seat pan air cells forming the thigh panel underlayment with an additional excursion which follows under experimenter selection, either the aircraft roll acceleration magnitude or roll velocity magnitude.

LAP BELT

The lap belt drive concept employs two informational sources: the orientation of the gravity vector projection on the XZ plane relative to the seat axis, and the orientation of the external force acceleration vector projection on the XZ plane relative to the seat axis. The latter excludes the effects of relative gravity orientation considered by the former.

Both vector projection orientations are employed in predetermined functions to arrive at separate lap belt force commands which are, in turn, summed. Either or both drive sources may be selected for evaluation by variance of the amount of total belt force allocated to each drive source.

The effect of the first drive source will cause the lap belt to contract as the seat and aircraft pitch over to the point where the subject is inverted, and relax again as an upright attitude is approached. Meanwhile, the second drive source abides by the external force acceleration projection so that belt contraction is experienced during loss of lift or sink periods and belt extension occurs during headwards acceleration periods. The lap belt does not respond to Y axis acceleration components.

GENERAL

It is plain from the preceding description that the basic drive concepts impose multiple excursion demands upon the individual air cells. Each concept is permitted to contribute, by a preset percentage controlled by the experimenter, to total cell excursion. Total cell excursion, therefore, is obtained as the algebraic sum of the excursion commands demanded by each concept.

The excursion characteristics of each cell, as driven by its respective pneumatic transducer, are maintained in array form and accessed by the software in computing the final drive commands issued to the linkage. These commands account for a subject weight of 160 pounds; should the weight of the subject differ radically from this value, drive rebiasing is established by the software upon manual input of subject weight.

Recognizing that the effects of the basic concepts can be blended, it is apparent that a large variety of seat pan, backrest, and thigh panel responses are available for a given acceleration vector. Figures 12 and 13 schematically represent the seat component responses expected for various representative acceleration vectors under the software control parameter configuration established for initial testing. In all of the schematics the solid line represents the seat component under normal 1 G conditions; the dotted line represents the component shape resulting from consideration of the sample acceleration.

Shortly after the completion of software generation the author inserted acceleration components representative of those which might exist for a hypothetical aircraft at various points in an unload and Immemann maneuver. Of interest were the commanded air cell positions and lap belt forces resulting from the activation of all G-seat drive concepts under the control parameter configuration established for initial testing. The results of that trial are displayed in Figure 14.

Located at the appropriate points on the maneuver is a group of 31 numbers arranged to graphically represent a planform of the G-seat air cells as viewed from above and behind the seat. Positive numbers represent cell excursion in inches above the midpoint, negative numbers represent cell excursion below the midpoint. Thigh panel excursion, which is pie-shaped, is measured in arc inches at the outer edge (edge opposite from the hinge line) of the thigh panels, positively and negatively from a 1-inch midpoint position.

Located adjacent to each "seat" graphical representation is a number representative of the commanded belt force above or below the normal "snug buckle-up" lap belt force (BUF).

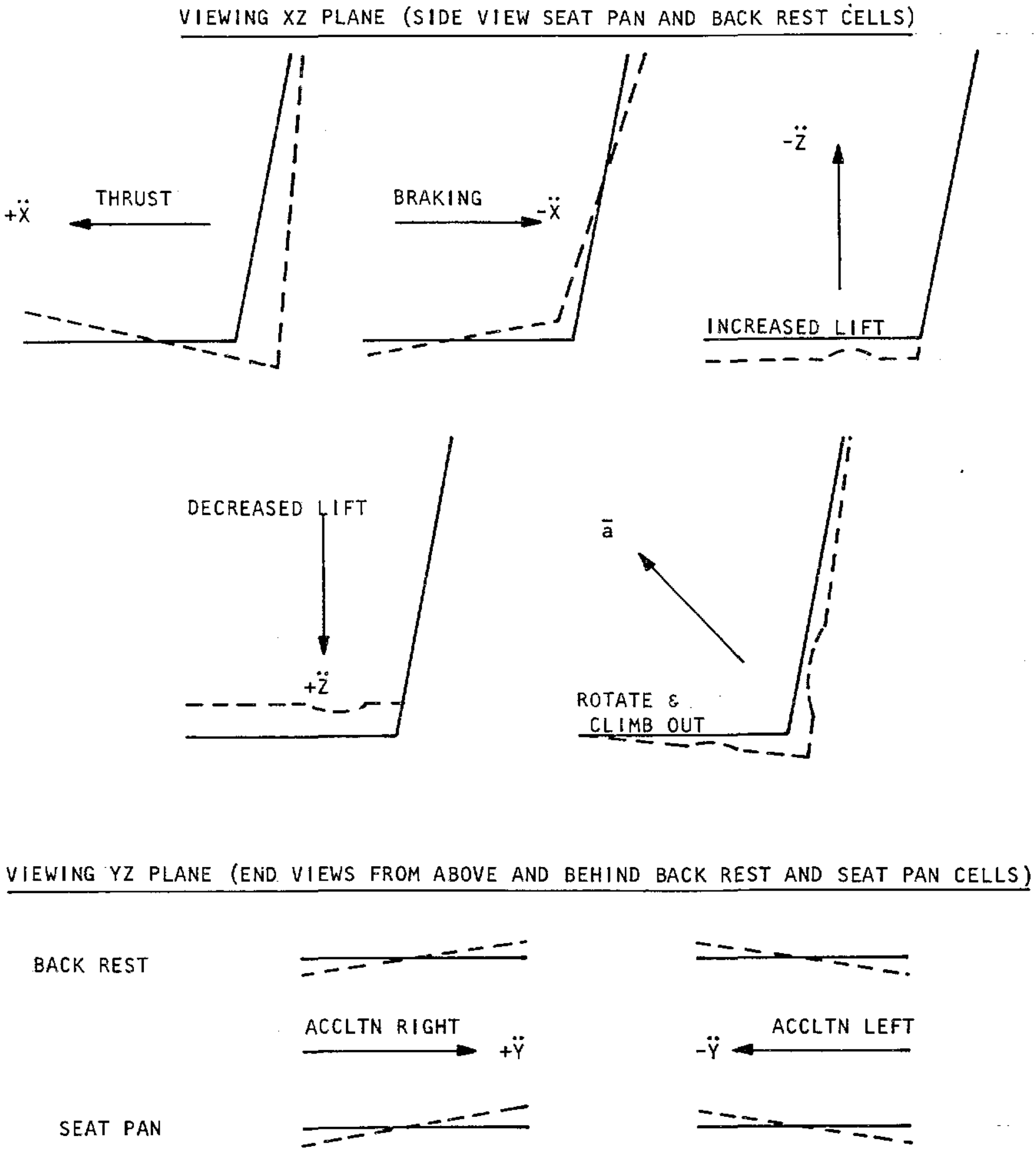


Figure 12 RESPONSE OF SEAT PAN AND BACK REST TO SELECTED ACCELERATION VECTORS

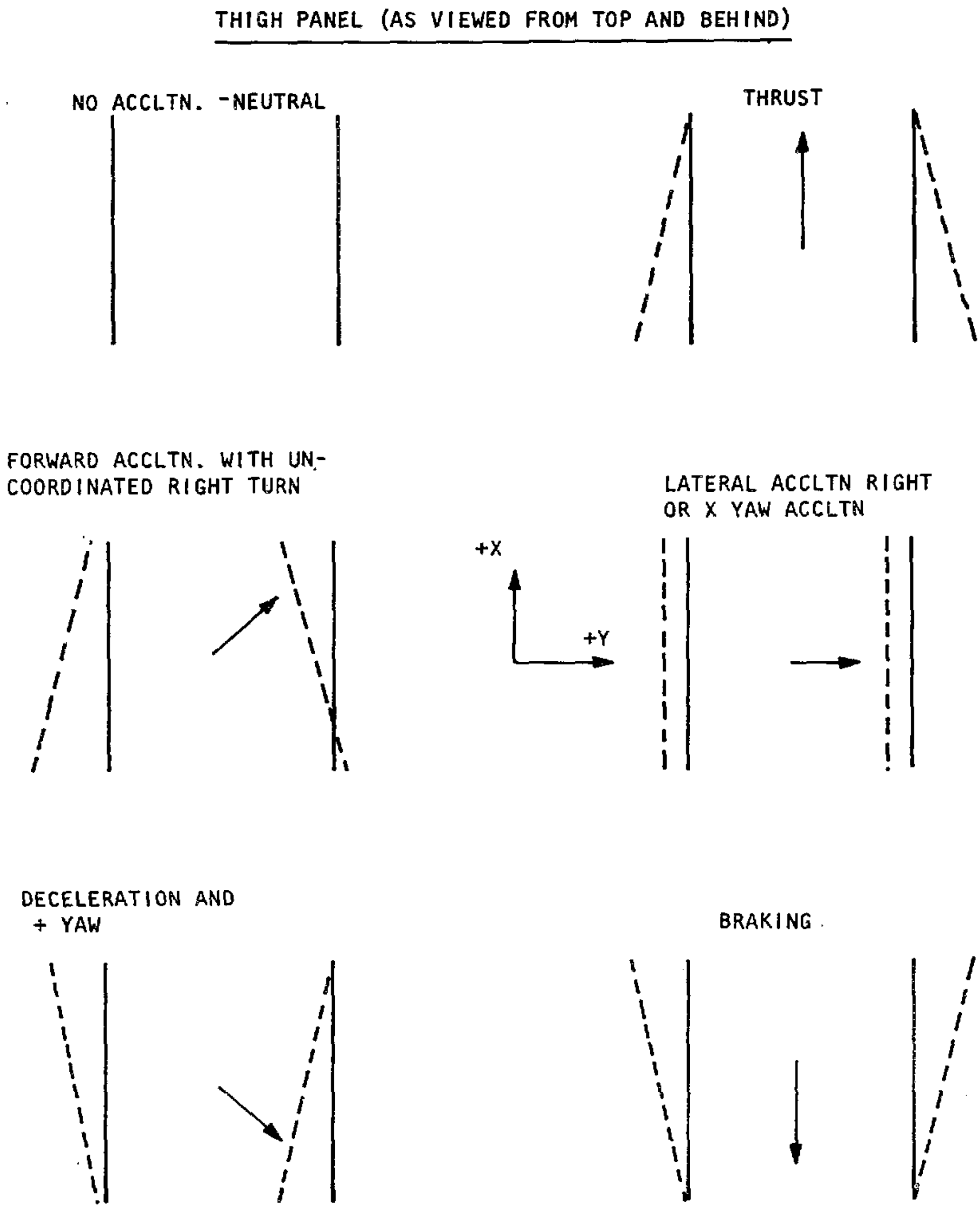


Figure 13 RESPONSE OF THIGH PANELS TO SELECTED ACCELERATION VECTORS

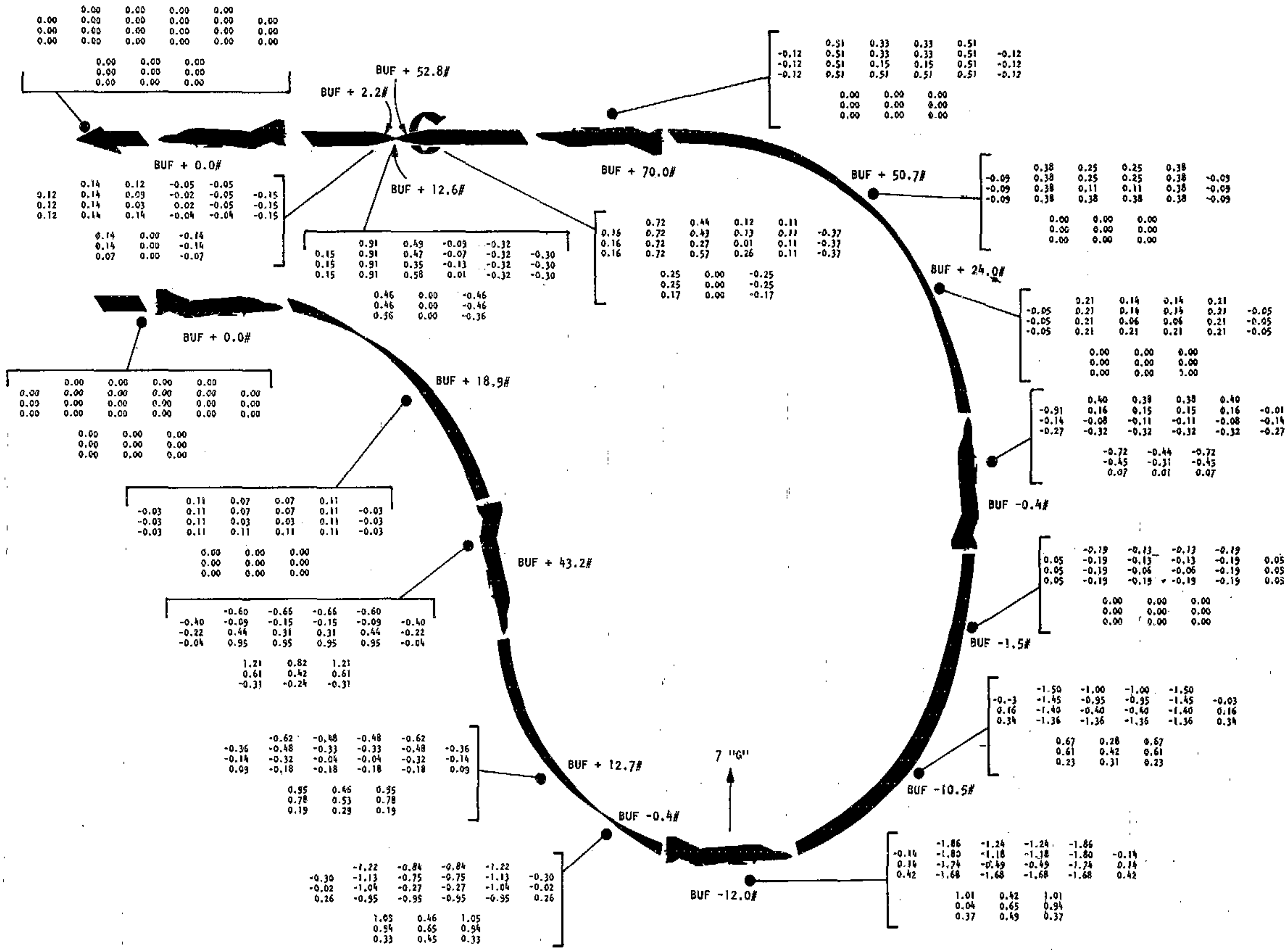


Figure 14 SOFTWARE COMMANDS FOR UNLOAD AND IMMELMANN MANEUVER

By moving from one seat "snapshot" to the next, the reader should be able to perceive the nature of seat movement throughout the maneuver. The maneuver also revealed that during high G loading conditions, the initial software configuration occasionally made excessive excursion demands of the air cells. Although command limiting exists to protect the air cells, concept intensity factors would be reduced slightly to eliminate overdrive conditions.

RESEARCH CONTROL

CONTROL PARAMETERS

Each of the basic G-seat drive concepts contain control parameters which may be easily altered by the experimenter for the purposes of haptic system stimulus evaluation. By way of example, these parameters provide the following latitude of control:

1) Permit each concept, on a per-axis basis, to be included or deleted from the overall drive scheme.

2) Permit the intensity of each concept, on a per-axis basis, to be varied.

3) Permit drive reversal within each concept on a per-axis basis.

4) Permit altering of the maximum anticipated acceleration components to which all of the concepts are scaled.

5) Permit decoupling of the effects of concepts which are interrelated, such as lap belt force and seat pan and backrest elevation.

6) Alter the source of drive, such as in the rotational concept wherein the drive source may be either aircraft roll acceleration or roll velocity.

7) Establish acceleration thresholds below which no G-seat response is desired.

The control parameters are maintained in software files for ready retrieval at the wish of the experimenter. It is therefore possible for the experimenter, in situations where comparative comment or analysis is desired, to alter the complete structure of the G-seat drive model in real time without imposing long reinitialization delays upon his subject.

CRT DISPLAY BENEFIT

One of the earmarks of the research mission of the ASUPT simulation complex is the presence of an extensive CRT system with which the experimenter may access and monitor and control software status. The CRT system possesses color capability and can present graphical displays as well as alphanumeric data. Keyboard entry units as well as display units are located in both cockpits for instructor utilization as well as at the advanced instructor station console normally considered the base for the experimenter. The CRT system is not part of the G-seat system but G-seat experimentation will be facilitated through utilization of the CRT system capabilities.

Since there are nearly 60 primary control parameters governing the G-seat software configuration, the experimenter must be provided a means to monitor and quickly recognize the configuration currently in effect. To this end the experimenter may activate a real-time CRT display which, by the use of color, schematics, and alphanumeric display, provides an overview of the current conceptual composition of the G-seat drive model. The display is updated whenever any G-seat control parameter is altered.

Figure 15 is a reproduction of this display and contains the value of the control parameters associated with the initial software configuration. Briefly, the schematic pictures an acceleration source to the left, along with data pertinent to maximum anticipated accelerations and desired thresholds. In the center appear only those individual G-seat software drive concepts currently in use, and clustered about each concept is data pertinent to the intensity of each concept. The conceptual lines are differently colored and easily traced to the right, where they terminate at the graphical representation of the seat component affected by the respective concept. The conceptual lines terminate with the amount of component excursion allocated to the concept.

To further aid the experimenter in understanding the effects of his decisions regarding the altering of control parameters, a second CRT display is available which monitors, in graphic form, the seat pan, backrest, and thigh panel air cell excursion currently commanded by the software. This display, updated once per second, is depicted in Figure 16. The author regrets that color reproduction of this figure is not available, for part of the display information is transferred through color recognition.

The display represents a planform of the G-seat air cells as viewed from above and behind the seat. Cell excursion is graphically portrayed by a three-color display. Cells currently commanded to the neutral point appear in yellow, those commanded above the neutral point appear in red, and those below the neutral point appear in green. The intensity of the latter two colors varies, on a per-cell basis, in proportion to the magnitude of the commanded excursion. This is accomplished by selectively painting the cell with different graphic symbols which activate different numbers of color triads in the construction of the selected graphic character.

Inset within the schematic representation of each cell is a numerical display of cell excursion in inches. This is the basic unit used by the experimenter in associating seat response with control parameter variation.

PRELIMINARY OBSERVATIONS

As of this writing, the prototype G-seat is in the initial stages of cockpit installation and test. Although additional work is required prior to complete checkout, the author has exercised the seat under flight software induced accelerations as well as with an acceleration driver ancillary program. The latter has been quite valuable in that acceleration profiles of known magnitude and shape and of a repetitive nature may be input to the software and left operating while altering the G-seat drive concepts. To date, all G-seat testing involving the cockpit installed seat has been conducted in the absence of "window scene" visual inputs or motion platform movement.

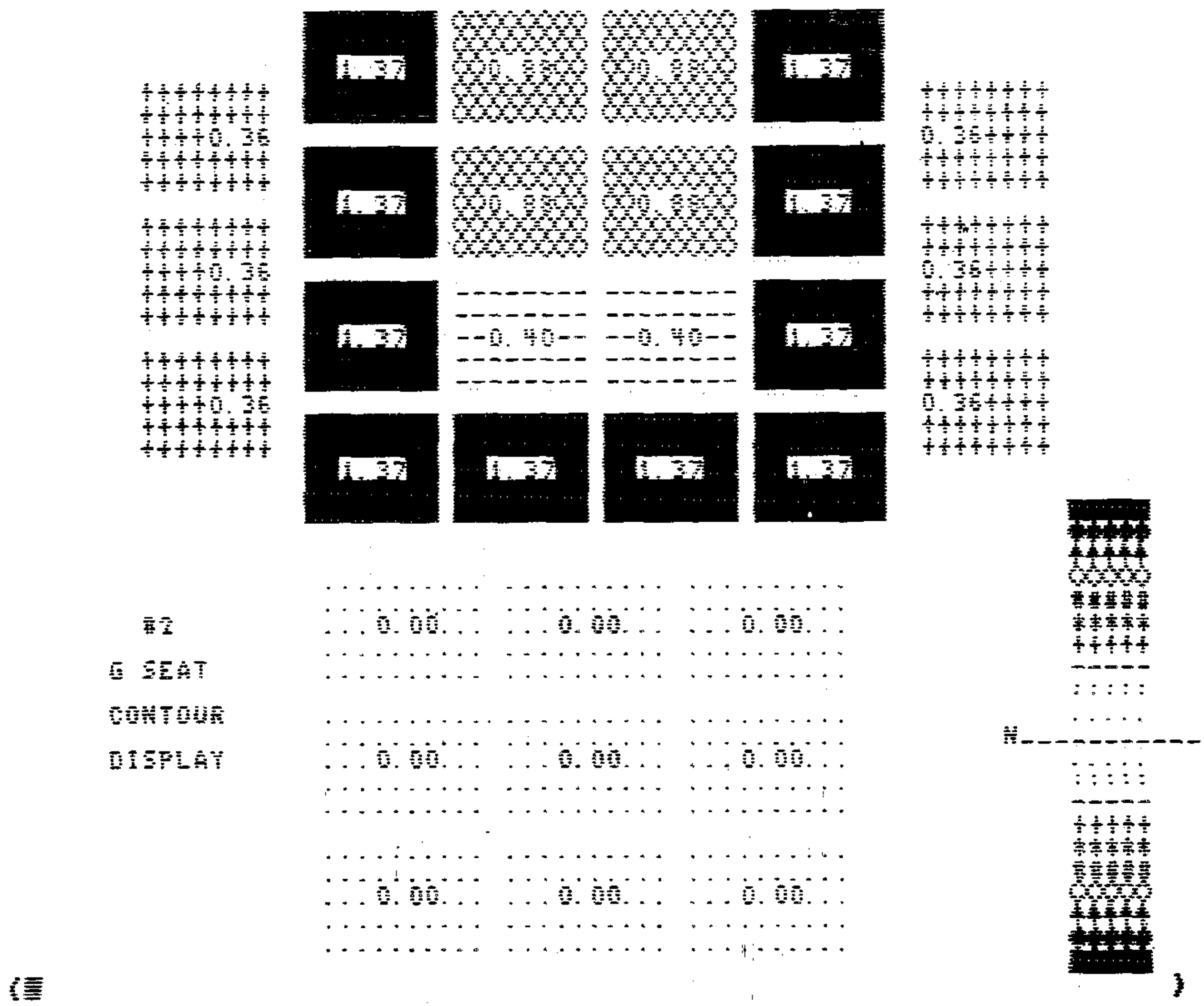


Figure 16 G-SEAT CONTOUR CRT DISPLAY

With respect to the seat hardware, the incorporation of tensile spring rates within each cell's excursion has been quite successful in producing a seat that "feels like a seat" rather than the sensation associated with sitting on an inflated rubber cushion. In the author's opinion, sitting in the G-seat is very much like sitting in a slightly firmer than normal standard upholstered office chair. The comparison may also be extended to feedback sensations affiliated with movement within the seat. As expected the incorporation of firm bellows top plates appears to have eliminated conflicting flesh pressure and skeletal attitude realignment sensations.

Seat movement is quite smooth. Low magnitude accelerations riding on the basic acceleration component profiles is not apparent in seat sensation. Although low-frequency movement of the type asscoiated with large long term acceleration profiles are of initial interest, as checkout proceeds, the useful frequency range, in terms of perceived oscillation, of the seat/foam padding/upholstery/flesh combination will be determined. The author has noted that seat movement to induce flesh pressure changes is more apparent, in terms of movement known to originate from the seat, than movement inducing skeletal attitude changes. It should be noted that this observation was made under conditions of zero or extremely low task loading by one who was preoccupied with, and concentrating on, seat response. As task loading materializes and concentration emphasis shifts to flying the aircraft, the author has noticed that "seat moving" sensations diminish.

Cushion movement is free of any perceptible pneumatic sounds emanating from the seat itself. By listening carefully the subject can hear the pneumatic control assembly, located outside the cockpit some 10-12 feet below the subject, respond to software commands. The author believes a sound abatement quilt loosely fitted over the pneumatic transducer racks will sufficiently isolate this source of sound as well as provide further dust protection for the transducer values. The only unusual seat sound noted to date is a very infrequent soft metallic sound resembling the sound of an innerspring when flexed. The sound emanates from the backrest and its decreasing frequency of occurrence is indicative of a "break in" characteristic.

The G-seat software drive model flexibility characteristics are currently being used to alter the drive scheme. The ability to input changes to the software control parameters and alter the driving acceleration profiles via the cockpit keyboard input and CRT display while simultaneously occupying the G-seat has proved to provide a very versatile method of improving upon the quality of the G-seat drive philosophy. A few observations leading to tentatively scheduled changes to the initial drive configuration are in order; however, the author wishes to stress the tentative nature of these changes since they are the product of only one person's opinion of what "feels better" rather than on the task performance level of a large group of subjects.

The inverted pendulum effect associated with lateral and longitudinal accelerations seems to be a very important cue. The author hypothesizes that the importance of this cue is due in part to the very noticeable shift in eye point as the upper torso pitches and rolls about the lower torso. Longitudinal accelerations produce a noticeable movement of the peripheral view, and lateral accelerations produce a noticeable shift in the parallax resulting from viewing the cockpit instruments and stick.

The initial drive configuration attempted to cause the bulk of the torso to settle deeper into the backrest cushion under positive longitudinal acceleration; however, in the absence of an active motion base the desired bodily movement would not occur and a penalty in terms of improper skeletal attitude shift resulted. By reversing the sign sense of the backrest attitude and translational drive, the response to longitudinal accelerations — for instance, that of upper torso pitch forward under negative acceleration complemented by a decrease in lower back/backrest cushion proximity awareness — seems vastly improved.

The inverted pendulum response to lateral acceleration induced by seat pan and backrest attitude changes seems proper; however, thigh panel response to lateral acceleration was scheduled to intensify the skeletal attitude shift. The seat pan attitude change alone appears to provide more than enough skeletal attitude change, and the author has found that reversing the thigh panel response to lateral acceleration produces the desired effect of increasing area of flesh contact on the side of the seat opposite to the acceleration vector direction.

Seat response to vertical acceleration components seems quite credible, and no changes in this portion of the total drive scheme are currently anticipated. Again the complementary eye point shift appears to enhance the sensation available from the seat.

The author has not yet investigated lap belt sensation and roll response and therefore can offer no preliminary observations concerning these two drive philosophies.

SUMMARY AND CONCLUSIONS

Aircraft simulators employ motion systems for the purpose of improving trainee piloting performance by providing a semblance of the stimuli thought to be employed by the trainee during execution of the actual task of piloting an aircraft. Motion is perceived through stimulation of the subjects' visual, vestibular, and haptic, or "body feel", sensory systems. The impact of stimulus reinforcement between these sensory systems has become of increasing interest to persons concerned with the art of simulation and has raised the question as to whether stimulation of the haptic sensory system by a device designed strictly for this purpose might improve the fidelity of motion simulation and/or reduce the demands placed on the motion base.

To initiate research directly aimed at investigating the role and importance of haptic system stimuli, a research oriented G-seat device has been developed to be used within the ASUPT Research Facility. The G-seat is designed to provide, in the absence of inertially caused body movement, stimuli to four haptic sensory system elements: skeletal attitude receptor mechanisms, muscle receptors, deep flesh pressure receptors, and cutaneous touch receptors. These are considered to be likely kinesthetic receptors, particularly in the presence of large magnitude long-term accelerations.

In order to elicit haptic system response, the seat employs movable seat pan, backrest, and thigh panel cushions, as well as a lap belt capable of being driven in extension and contraction. To provide the versatility required of a research tool, the G-seat cushions are constructed of air cells arranged in mosaic form so that a broad range of cushion surface attitudes shapes and elevations may be commanded.

A pneumatic control assembly providing individual pressure control of each one of the 31 drivable cushion-elements as well as the lap belt actuator responds to G-seat software drive commands with pressure changes which are continuous in nature. A general-purpose G-seat drive signal model software package provides seat control according to the precepts of a number of concepts, the intensity and composition of which the experimenter controls by variation of easily altered control parameters.

The G-seat development phase demonstrated serious liabilities in attempting to elicit credible haptic sensory stimuli with pliable plastic air cells restrained solely by the weight of the subject. The design was altered to implement metal air bellows which display a rigid surface to the contacted flesh and the software expanded to provide contouring effects for the purposes of driving flesh pressure receptors. Tensile spring rates were incorporated in the design of each mosaic element to provide a stiffer, more predictable seat cushion form under conditions of subject activity within the seat and inter-subject physiological variations among subjects.

The preliminary results have caused the author to conclude that the above mentioned basic changes made in air cell design satisfactorily eliminate the earlier objections incurred in pliable air cell use. Further, the mosaic form of cushion construction has proved to provide a practical method of achieving variation in seat response. The seat visual appearance and absence of seat affiliated pneumatic sounds leads the author to believe that the environmental fidelity of the cockpit is preserved and there should be little or no ongoing overt reminder of, and resultant preoccupation with, the presence of an "unusual" seat.

It is apparent even from the brief exercise of the total G-seat system conducted so far that the system offers the experimenter the type of hardware/software flexibility required to begin investigation of the importance of haptic sensory system stimuli to kinesthetic determination. Many of the sensations available from the seat appear to improve the fidelity of the large-scale long-term acceleration environment, which in itself may be instrumental in maintaining productive interest levels on the part of experienced pilots returning to the simulator for piloting performance verification. One of the products of the research effort will be an assessment of transfer of training available through G-seat usage, and this will form an important measure of the value of G-seat systems in future training simulators.

BIBLIOGRAPHY

1. Brown, J.H.U. Physiology of Man in Space. Academic Press; 1963

2. Gibson, J. J. The Senses Considered as Perceptual Systems. Houghton Miffin Co., 1966.

3. Hertzberg, H. T. E. Annotated Bibliography of Applied Physical Anthropology in Human Engineering. Aero Medical Laboratory, Wright-Patterson Air Force Base, Ohio. WADC Technical Report 56-30; 1958.

4. Howard, I. P. and Templeton, W. B. Human Spatial Orientation. Wiley & Sons; 1966.

5. Lay, W. E. and Fisher, L. C. Riding Comfort and Cushions. Society of Automotive Engineers Journal (Transactions), Vol. 47, No. 5, 1940, pp. 482-496.

6. Mueller, C. G. Sensory Psychology. Prentice-Hall; 1965.

7. Physiology of Flight. Air Force Pamphlet No. 161-16; 1963.

8. Woodson, W. E. and Conover, D. W. Human Engineering Guide for Equipment Designers. University of California Press; 1966.

9. Gum, D. R., Modeling of the Human Force and Motion Sensing Mechanisms. Thesis, Ohio State University, 1972.

10. Kron, G. J. Future Undergraduate Pilot Training, Study - Report A Fidelity of Aircraft Simulation of Appendix II Simulation Requirements and Technology; Lockheed - California Company Report No LR23918-2 under Contract No. F33615-70-C-1141; February 1971.

NOTE

The research G-Seat system discussed herein is currently in the process of being tested and readied for operation. Due to the schedule required for preparation and submission of papers, this report contains observations of G-Seat performance which are of a preliminary nature. It is anticipated that during the next few months more concrete results concerning G-Seat operation will become available and would be reported at the November 1973 Naval Training Equipment Center Conference. The document forms a necessary foundation for discussion of G-Seat performance.

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