

Gravitational-Cueing System—An Enhancement of Aircraft Flight Simulation

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This paper describes a man-machine interface that is used in aircraft trainers to create artificial acceleration cues, which are perceived by the pilot as the cues produced by real environmental effects. This interface, designated as the gravitational cueing (g-cueing) system, translates acceleration components generated in an aerodynamic math model into cues that create sensations experienced in a real aircraft. The g-cueing system is a microprocessor controlled, hydraulically and pneumatically actuated, stand-alone system that can enhance the realism of the simulated flight environment.

Designers of modern aircraft simulators are striving to perfect a man-machine interface capable of producing artificial kinesthetic cues that will be perceived by the pilot as the effects of physical forces. One such interface, which creates cues analogous to gravitational forces, is the gravitational cueing (g-cueing) system.

The g-cueing system replaces the six-degree-of-freedom motion system that has been used in recent years to simulate aircraft motion. The main difference between a six-degree-of-freedom motion system and a g-cueing system is that the former subjects the entire cockpit to motion, but the latter only deflects sections of the pilot's seat and backrest to produce sensations of motion.

FUNCTIONAL DESCRIPTION

In the real environment (with actual aircraft), motion is measured in hundreds of kilometers per hour and distances traveled are measured in thousands of kilometers. In the simulated flight environment, motion is confined to centimeters per second and distances of a few centimeters. This disparity may suggest that it would be impossible to simulate aircraft motion in a simulated flight. However, for a person within the flying aircraft, where there exists no visual frame of reference, the entire airframe appears only to vibrate while suspended in space and no motion is apparent. This exact sensation can be duplicated by subjecting the pilot's seat to only a few centimeters of physical motion. This limited motion is all that is necessary to generate vibration and buffet cues and linear and angular acceleration cues. Acceleration cues can be classified as sustained acceleration cues and onset acceleration cues. Sustained acceleration cues are experienced during a gradual and continuous turn, climb, or dive. Onset acceleration cues are experienced during sudden changes of motion.

The g-cueing system provides the pilot with the sensation of motion, which enhances the simulated cockpit environment during a simulated flight. The motion cues generated by the g-cueing system are functions of stimuli that are generated by pilot manipulation of aircraft cockpit controls or by aircraft systems interactions that affect the simulated aerodynamics. Motion cues are perceived by the pilot through his or her vestibular sensory system. Motion cues can be classified into three categories: (a) directed translation, (b) vibration, and (c) acceleration.

PHYSICAL DESCRIPTION

The g-cueing system consists of several components. Some components are directly involved with the gen-

eration of the cues; others are ancillary equipment. Components that are directly involved in the generation of the cues can be divided into three categories: (a) active elements, (b) passive elements, and (c) functional elements.

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

Functional elements are components that perform specific functions in the real aircraft cockpit and are incorporated in the simulator to create a more realistic environment. All functional elements must perform identical functions in both the real aircraft and the simulator.

Some elements of the g-cueing system can have a dual role in the g-cueing system. For example, the lap belt is a passive element when it is used to restrain the pilot in the seat. When the belt is mechanically caused to tense or scrub on the pilot's anatomy, which creates a cue, it assumes an active role.

G-Seat Assembly

The g-seat assembly (see Figure 1) is the most important element in the g-cueing system. It consists of a modified aircraft ejection seat and its accessories. A passive survival kit belt, a functional shoulder harness, and a functional seat height positioning mechanism are accessories of the g-seat assembly that were preserved from the aircraft seat to enhance the simulated environment.

The active elements of the g-seat assembly are introduced by modification of the seat pan and backrest. This modification involves the replacement of the seat pan and backrest with movable plates. Three actuators are attached to each of the two movable plates (see Figures 2 and 3). The actuators produce a heave motion when actuated together or a rotational motion when actuated differentially.

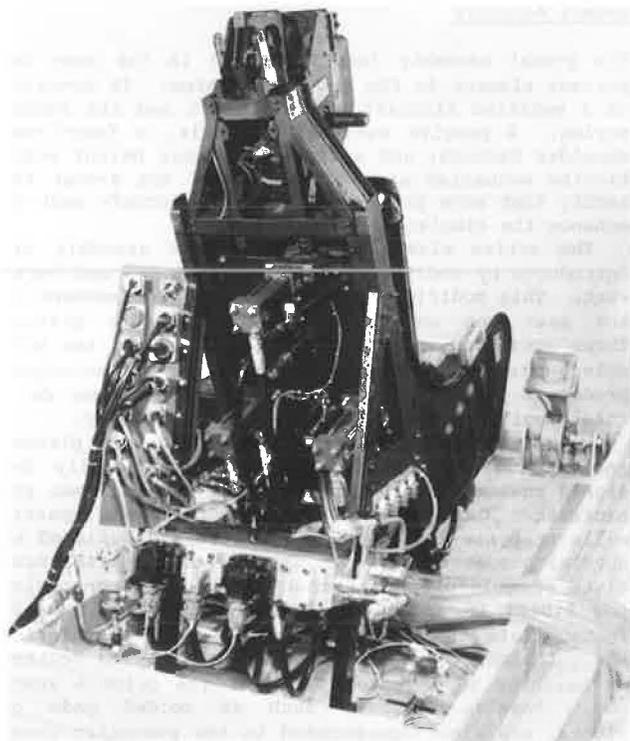
In addition to the seat pan and backrest plates, the modification includes a pair of specially designed pneumatic cushions that line the seat pan and backrest. Each cushion consists of four separate cells that are individually inflated and deflated by special pneumatic valves. The cushion material consists of multiple cells that incorporate constraining fibers to reduce bowing and ballooning effects. Like the actuators, which cause translation and rotation, the cushions can cause varying degrees of hardness to selected parts of the pilot's anatomy. Passive devices, such as molded pads or blocks, are also incorporated in the pneumatic cushions to provide movement and pressure cues to the pilot's buttocks and thighs (see Figure 4).

The seat pan actuators produce a three-degree-of-freedom motion (i.e., heave, roll, and pitch). This motion can be represented by the combined excursion of the hydraulic actuators (± 2.54 cm) and the variable thickness of the seat cushion (± 1.28 cm). In the quiescent state, the seat is ± 3.84 cm from the zero position. When activated simulta-

Figure 1. G-seat assembly, front view

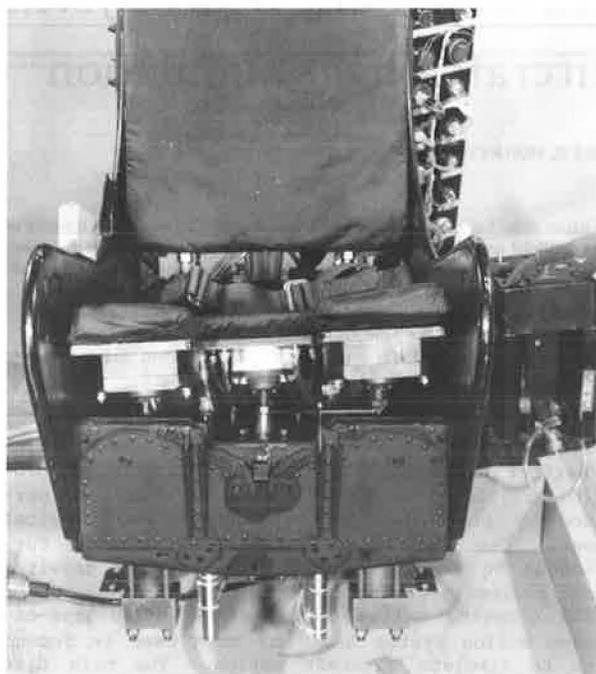


Figure 2. G-seat assembly, rear view.



neously and equally, the three hydraulic actuators cause a heave motion. When one actuator is activated in the positive direction and the opposite actuator is activated in the negative direction, a rolling motion is produced. When the rear actuators

Figure 3. G-cueing seat, front view.



are activated in the opposite direction from the front actuator, a pitch motion is produced.

The backrest active elements produce an additional three-degree-of-freedom motion. When all three actuators are activated simultaneously and equally, a longitudinal motion (forward to back) is produced. This motion is also confined to the ± 2.54 cm traveled by the actuators. When the backrest hydraulic actuators are activated differentially and in opposite directions, a yaw or pitch rotational motion is produced.

The backrest cushion operates the same as the seat pan cushion. It provides ± 1.28 cm of motion to the backrest due to the variable thickness of the cushion. Linear transducers are mounted on each of the six hydraulic actuators (three seat pan and three backrest), and pressure transducers are mounted in each of the eight cells (four seat pan and four backrest) of the two pneumatic cushions. The transducers provide a closed-loop monitoring system for the g-cueing microcontroller.

Active Lap Belt

The lap belt is a functional component of the real aircraft seat. The belt is incorporated in the simulated cockpit as a passive element of the g-cueing system. In the g-cueing system, under certain conditions, the lap belt also behaves as an active element and produces important motion cues. In the g-cueing system, both ends of the lap belt are anchored to hydraulic actuators. When both actuators are activated equally, a force is applied to the pilot's abdomen, which produces a sensation that is similar to the one experienced in a negative g-acceleration maneuver (aircraft dropping). Conversely, in a positive g-acceleration condition, the belt is loosened and few, if any, cues are generated. When driven differentially, the belt provides the scrubbing sensation that is experienced during lateral and yaw maneuvers.

Figure 4. G-cueing seat pan cushion.



Figure 5. Helmet loader.



Helmet Loader

The helmet worn by the pilot in the real aircraft can be used as an active element in the g-cueing system. Two flexible wire cables are attached to each side of the helmet and anchored at the opposite ends to two motor-driven reels (see Figure 5). Commands from the microcontroller drive the two motors, which reel in part of the cable and cause a force toward the pilot's shoulders. This effect is simi-

lar to the weight of the helmet increasing in direct proportion to the gravitational forces.

G-Suit

The g-suit, which is a functional component of the real aircraft, is used to prevent a rush of blood from the brain that could cause blackouts or tunnel vision during high acceleration conditions. The g-suit incorporated in the g-cueing system is an active element. Even though blackouts or other ill effects cannot be generated by the g-cueing system, the g-suit provides the necessary cues that are normally associated with high acceleration conditions. The g-suit is connected to pneumatic and vacuum supplies. In response to the proper command from the microcontroller, the suit inflates or deflates to simulate the discomfort experienced under real flight conditions. The vacuum supply is used to enhance the response of the suit during deflation.

G-Cueing Microcontroller

The g-cueing microcontroller is a specially designed processor and signal conversion unit (see Figure 6) that comprises a pair of state-of-the-art microprocessors and the associated solid-state memory. One of the two microprocessors is a fixed instruction, 16-bit microprocessor designed around a 9900 integrated circuit. This microprocessor provides executive control functions for the entire g-cueing system and is designated as the controller microprocessor unit (MPU). The second microprocessor in the g-cueing microcontroller is a bipolar, bit-slice, microprogrammable device that provides the extremely high computation speeds required for a real-time computation application. This microprocessor is used for arithmetic processing and is designated as the arithmetic MPU. The two microprocessors intercommunicate via shared memory.

Conversion Hardware

The conversion hardware consists of special digital-to-analog conversion (DAC) and analog-to-digital conversion (ADC) cards. The DAC cards are used to translate digital commands to analog signals applied to the servo amplifiers, which drive the hydraulic and pneumatic actuators. The ADC cards provide actuator position feedback to the controller MPU. The cards are bipolar, ± 10 volt, full-scale, and provide a 12-bit resolution.

OPERATIONAL DESCRIPTION

G-Seat Dynamics

The g-seat assembly is electronically controlled and hydraulically and pneumatically powered. The electronic control is provided by a microprocessor controller. The microcontroller receives stimuli from a mathematical model of simulated aircraft aerodynamics. From these stimuli, the microcontroller computes the necessary commands that enable the seat actuators to produce the required cues.

System Response

In general, the hydraulic actuators generate onset acceleration cues, and the pneumatic cushions generate sustained acceleration cues. Onset cues are experienced during sudden changes in acceleration (amplitude or direction), and only a hydraulic actuator can provide the required response.

The pneumatic cushions provide the cues in a sustained acceleration maneuver. Sustained accelera-

Figure 6. Microcontroller block diagram.

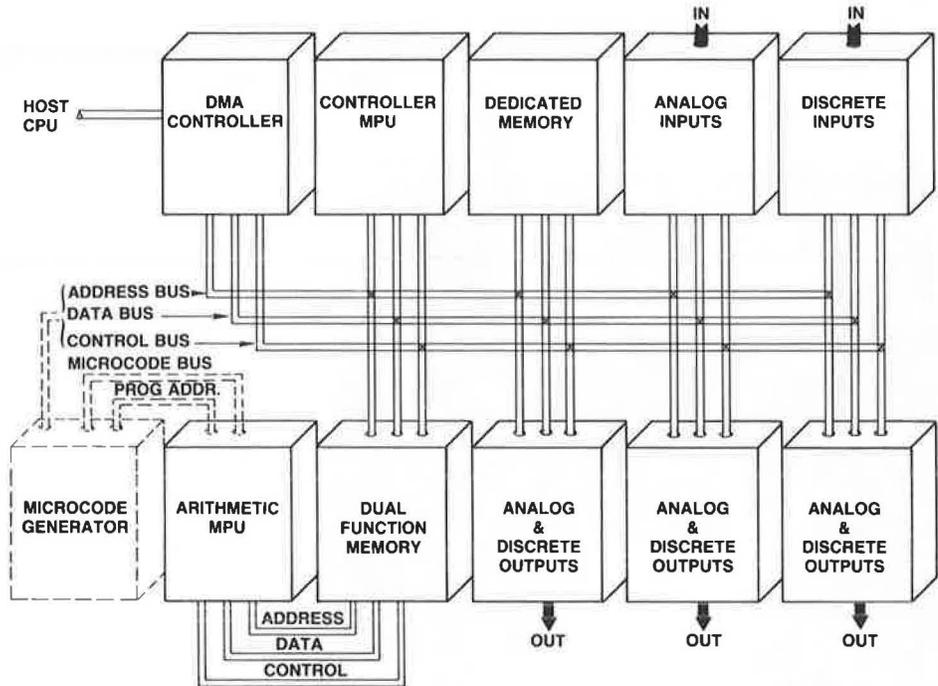
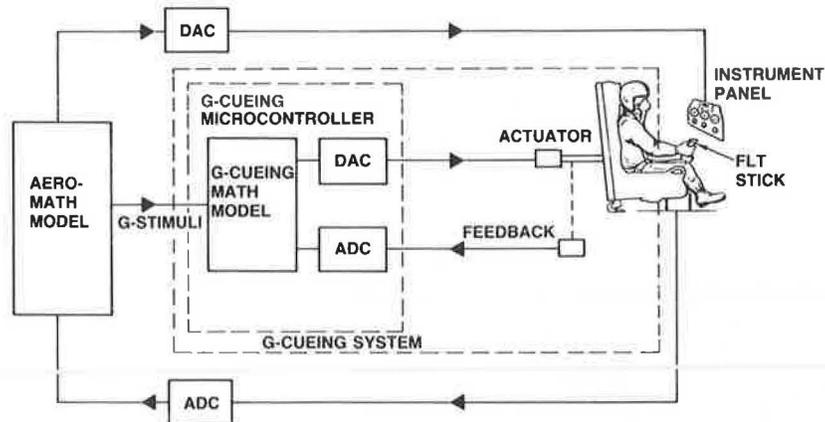


Figure 7. G-cueing system block diagram.



tion cues are experienced when the aircraft is in a gradual and continuous turn, climb, or dive. The cues experienced during such maneuvers are primarily firmness of a section of the seat and a pull on the lap belt. The pneumatic system consists of a pneumatic power supply and four valves per cushion. A special valve and a vacuum supply are used to enhance the response of the g-suit. Primary cues in the g-seat are caused by the hydraulic actuators as onset acceleration cues. These cues are the result of complex coordinated maneuvers of the aircraft, which are translated by the mathematical models into commands to the actuators. A set of secondary cues can be produced by selectively varying the hardness of the seat pan and backrest cushions. Secondary cues are used to simulate sustained acceleration.

The active elements of the g-seat provide a maximum motion of ± 3.84 cm. Of this distance, ± 2.54 cm is produced by the hydraulic actuators. The remaining ± 1.28 cm is produced by varying the cushion thickness.

In addition to the complex composite cues produced by the aerodynamic equations, vibration and buffet cues can also be introduced through the hy-

draulic actuators. These vibrations consist of combinations of sine-wave signals modulated by preprogrammed envelopes that are generated by the g-cueing mathematical model.

G-Cueing Control

To produce meaningful commands to the various elements of the g-cueing system, which in turn produce composite cues, a mathematical g-cueing model is employed. The mathematical model is contained in a specially designed processor designated as the g-cueing microcontroller. The g-cueing microcontroller is interfaced with and derives the g-cueing stimuli from the aircraft aerodynamic mathematical model. The stimuli consist of load forces that are proportional to the linear and angular accelerations. The load forces are translated into special commands, which are in turn converted to analog signals. These analog signals provide the driving voltages to the hydraulic and pneumatic actuators to produce the corresponding cues. A simplified diagram of the microcontroller-g-seat relationship is shown in Figure 7.

Mathematical G-Cueing Model

The mathematical g-cueing model resides in the microcontroller. This model consists of 29 program models. The mathematical model translates the acceleration control forces stimuli into meaningful commands to the actuators to provide for the proper cues. The various program modules provide for stimuli scaling, integration, interpolation, initialization, fade in and fade out, curve shaping, seat dynamics, and many other control functions.

Simulated Motions

The various actuators produce multiple motion cues simultaneously, as demanded by the flight equations of motion. Listed below are some of the various maneuvers and analogous cues that can be produced by the g-cueing system:

1. Buffet,
2. Stalls,
3. Dives,
4. Climbs,
5. Banks,
6. Spins,
7. Rolls,
8. Vibrations,
9. The sensation of release of stores (e.g., bombs and rockets),
10. Touchdown,
11. Impact,
12. Airbrake application,
13. Landing gear strut dynamics,
14. Ground taxiing including runway rumble, and
15. Landing gear motion.

POTENTIAL PROBLEMS

Eye-Level Shift

In normal level flight, the pilot's eyes lie in a plane parallel to the horizontal, and he or she views the various instruments and displays by simple head and eye motions. During high acceleration maneuvers, the relative level of the pilot's eyes, with respect to the instruments, remains the same (except for approximately 1.28 cm due to thoracic contraction). In the g-cueing simulated environment, the pilot's body is raised and lowered relative to the instruments. This relative positioning of the g-seat can cause exaggerated shift of eye level, which results in negative training. The hydraulically activated seat pan and the pneumatically inflated seat cushion can be moved in opposite directions to compensate for exaggerated eye-level shift.

Pilot Weight Bias

Since all pilots do not weigh the same, body contact with the seat and the sensation of firmness can vary

from pilot to pilot. Provisions for the instructor to enter the pilot's weight into the mathematical model alleviates this problem. The 1-g reference, with regard to seat firmness, area of body contact, and quiescent level, is established at system initialization, prior to the start of a mission.

CURRENT STATUS

The g-cueing system described in this paper, less the helmet loader, is contracted for installation in six F-15 aircraft simulators being manufactured for the Royal Saudi Air Force and the U.S. Air Force (USAF). All preliminary studies and evaluation were performed on a laboratory prototype system by using the F-15 aircraft aerodynamic mathematical model as a driver. The g-cueing system has been evaluated by USAF and Navy pilots and many nonmilitary personnel. Most of the pilots had experience on a six-degree-of-freedom motion-platform simulator, although not all pilots had flown the F-15 aircraft. Their comments and critiques aided in the refinement of the mathematical g-cueing model. All pilots agreed that, due to the lack of preestablished guidelines and criteria, their evaluations were highly subjective.

Two pilots that flew the same mission expressed divergent views on specific cues. A majority of the criticism was directed at peripheral hardware (e.g., control stick feel forces, rudder pedals, and throttle quadrant) that, even though not part of the g-cueing system, if improperly simulated could distract and confuse the real cues.

Less-experienced pilots tended to limit their maneuvers to the range of 1 to 4 g's. The more-experienced pilots, and the F-15 pilots in particular, evaluated the performance of the g-cueing system in maneuvers of 4 to 7 g's. Each group wanted the cues to be exaggerated at their particular range. Some pilots felt that the roll maneuver of the seat pan should be reduced, and others indicated that an upper body sway should be added. Most recommendations resulted in changes in the g-cueing mathematical model, which resulted in improved performance characteristics.

CONCLUSION

All of the pilots who have evaluated the g-cueing model have lauded the response of the system and felt that it performed equal to or better than the six-degree-of-freedom motion system. They agreed that the primary cues were adequately simulated and felt that a more-critical evaluation will be possible in a completed simulator environment.

Publication of this paper sponsored by Committee on Simulation and Measurement of Driving.