Application and Implementation of Dynamic Motion Seats

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ABSTRACT

Over the last decade, advances in technology have contributed to the development of high fidelity, multi-channel, dynamic motion seats that can be integrated into new training devices or retrofitted for use in existing devices. These dynamic motion seats have also been introduced into select training devices for evaluation. This paper provides a brief history of dynamic motion seats including the development of seat cueing technology, summarizes the attributes of available seats, and discusses the factors associated with the implementation of the dynamic motion seat including physical issues and software issues. This is followed by a discussion, supported by empirical study results, describing the application of the seats in various training environments including rotary wing and fixed wing aircraft as well as in fixed-base and motion-based trainers. Evaluations of the use of dynamic motion seats in these environments concluded that the seats improve overall training effectiveness and the training of specific tasks.

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INTRODUCTION

The technology in today's dynamic motion seat offers the simulation industry a high fidelity, multi-axis motion cueing system in a compact and low cost package. This technology, coupled with the understanding of how motion cues improve training effectiveness, has lead to an increase in the use of motion seats. Dynamic motion seats are being integrated into variety of simulators to provide motion cueing on fixed-base trainers and to augment cues generated by motion platforms. They are being added to high fidelity military and general aviation simulators as well as low cost simulators such as locomotive and ground vehicles to increase the simulation fidelity and user acceptance.

Historically, the dynamic motion seat has had limited success in the simulation industry mainly due to limitations in the design and technology that have been applied to the devices. An examination of the studies performed on motion cueing systems throughout this period highlight the limitations of the past technology. However, the evolution of the dynamic motion seat from a simple G-seat with a pivoting seat pan and complex packaging to a small, efficient device providing cues in multiple axes has increased its acceptance and use throughout the training industry.

Integrating dynamic motion seat technology into new and existing simulators is easy. The seat's mechanical packaging is compact and uses electric motors as a motive force. The software interface uses standard network protocols. This allows users to implement motion cueing in a cost effective manner.

THE TRAINING ENVIRONMENT AND MOTION CUES

Environments of varying levels of dynamic fidelity are needed for training. At one extreme are fixed base simulators (which provide trainees with no motion cues). At the other extreme are live training events which provide high fidelity experiences but are very costly. Dynamic simulators employing various force cueing devices (e.g., motion platforms and dynamic motion seats) are designed to provide a degree of environmental realism, and fall somewhere between these extremes.

In live training events (the ultimate training environment) a trainee experiences various forces on the body that shape his/her control behavior. The forces provide cues about the motion of the system resulting from control input, system operation, and the environment (Heintzman, 1997; Szczepanski & Leland, 2000).

Three simulation technologies have historically been used to produce motion and force cues:

a. Visual systems to provide motion cues
b. Vestibular cues to invoke sensations of angular velocity
c. Haptic cues signaling continuous body loads to facilitate recognition of orientation

Simulation of motion is inherently difficult to create in a ground-based system because it requires the entire simulator (with trainee) to accelerate and move over a physical distance. Since the late 1970s, high fidelity aircraft simulations have induced motion cues by utilizing motion platforms to translate the entire simulation cab. By moving the cab, the motion platform indirectly affects the trainee. However, the motion platforms provide only small and very brief accelerations to excite vestibular cues. The platforms provide limited sustained haptic cueing for pitch, roll, longitudinal and lateral cues by tilting the platform and using the gravity vector. The six leg hexapod, or Stewart, motion platform has become the de facto standard in the simulation industry to provide these cues.

Dynamic motion seats provide haptic cues directly to the trainee, but do not produce vestibular cues. This is a fundamental difference between dynamic motion seats and motion platforms. The hexapod motion platform utilizes actuator legs to induce acceleration onset cues. The actuator legs extend or retract to physically translate the simulation cab providing the cue. Special washout algorithms, operated at accelerations below the trainee's sensory threshold, are used to provide actuator motion in the direction opposite to the onset cue, enabling the platform to return to the neutral position. Because of limited actuator displacement, the onset cues are limited in duration, frequency, and amplitude. Some analyses (Nahon, Ricard and Gosselin, 2004) have demonstrated that without proper implementation, the cues provided by motion platforms can be poorly correlated to a variety of training tasks. Furthermore, the hexapod platform has significant initial and recurring costs, although the utilization of electrically driven actuators has decreased this cost (Burki-Cohen and Sparko, 2007). Factors which cannot be modified by new technology are the constraints that the standard hexapod platform imposes on the facility. The excursion envelope of a high fidelity motion system and cab often requires a clear space approximately 13m wide by 13m long with a ceiling height exceeding 12m.

While a hexapod motion platform is designed with the single goal of accelerating the cab, dynamic motion seats have multiple goals including the following:

- Enhancing the fidelity of the simulation environment by providing the trainee with a seat that looks and feels like the seat of the actual vehicle
- Producing sustained acceleration cues for the trainee or enhancing the onset cues provided by a motion platform
- Producing kinesthetic sensations to simulate the vehicle motions

Dynamic motion seats also have significantly lower initial and recurring costs than large excursion hexapod motion platforms. The recurring initial cost of even the most complex motion seat is usually less than one-third the cost of a motion platform and imposes no particular constraints on the facility. While it has a complex mechanical design, the dynamic motion seat has to fit within the existing physical constraints of the vehicle cab since it emulates the actual vehicle seat. Furthermore, each seat has little accompanying equipment, often no more than a small electronics rack.

HISTORY OF MOTION SEAT DEVELOPMENT

Dynamic motion seats were developed around the same time period as the hexapod motion platform. Due to technological limitations, early dynamic motion seats were typically identified as ‘G-seats’ and they were designed to operate in essentially one or two axes (vertical and longitudinal). Early seat designs utilize two general design approaches:

- Upholstered, moveable plates driven through linkages by drive actuators
- Pneumatically powered seats constructed of soft pliable bladders and sometimes augmented with springs

Perhaps the best known and most widely used of the early seat designs was the pneumatically driven G-seat known as the Link seat. This seat design was introduced in late 1976 (Cardullo, Hewitt and Kron 1976) and utilized a matrix of pneumatic cells for the seat pan and back. To this were added thigh panels and a pneumatically driven lap belt. The seat was designed to emulate vertical G-loading using the seat pan and longitudinal accelerations using the seat back.

There were basic shortcomings with all early seat designs, regardless of the motive power. The early drive actuators were analog-based, which drifted over time, causing uncontrolled and unanticipated seat performance. Additionally, the components were physically large, which limited the implementation of multiple axis designs due to the constraint of the cab envelope. The pneumatically driven seats had additional issues. Because the motive force was based on a mosaic of individual bladders, conflicting trainee stimuli were produced (Ashworth, McKissick, 1984). The only force on a pneumatically driven seat is provided by body weight, so seat cushion ballooning can result. Furthermore, contradictory requirements of pressure in the bladders produced less than desired results.

Technological limitations caused performance shortfalls in the early motion seats. The only seat motive force with sufficient control and power were pneumatic or hydraulic based systems. The limitations of these systems manifest themselves in very complex assemblies with high maintenance requirements that imposed significant constraints on the required facilities because of required hydraulic power units, compressors, and vacuum systems.

Fortunately, time helps address technological limitations. With the advent of rare earth permanent magnets, small but powerful electric motors became the choice for seat motive power. By using modern precision drive motors coupled with bellcranks and push-pull linkages, the performance of modern dynamic seats is far superior to the early G-seats. Furthermore, modern seats operate in more than just vertical and longitudinal axes; they provide cues in multiple axes. Hence, the nomenclature changed from simple G-seats to the more comprehensive dynamic motion seats.

DYNAMIC MOTION SEAT TECHNOLOGY

Currently, the most sophisticated motion seats on the market utilize five axis force cueing with additional harness control to provide realistic kinesthetic (sense of movement) and haptic conditions to the trainee. To provide correlated cues, the seat moves in five independent axis of control using four axes of movement: vertical, longitudinal, lateral and roll. Figure 1 shows the relationship between these cues.

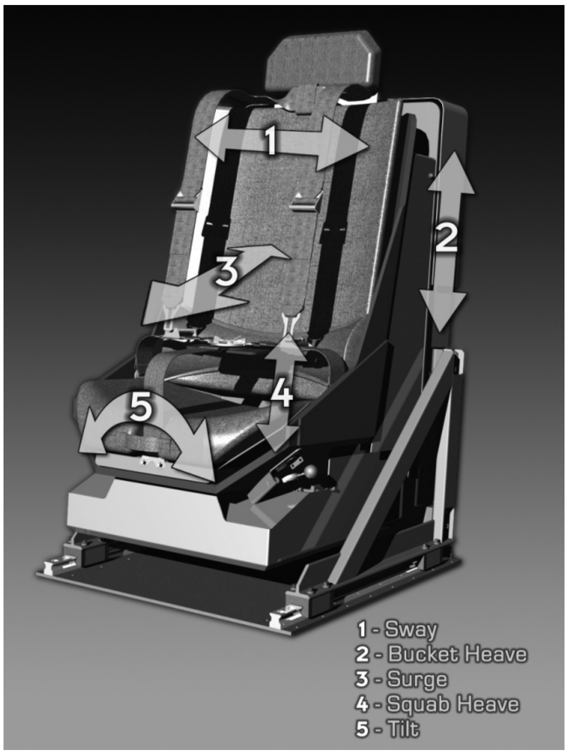

Figure 1 Direction of Movement in a Five-Axis Dynamic Motion Seat

Two independent actions are generated in the vertical axis: one action for the entire seat (bucket heave) and one action for the seat pan (squab heave). The trainee can also use bucket heave to adjust the height of the entire seat in the vertical axis. In addition to squab heave, the seat pan tilts side to side to induce roll effects. Simultaneous with the heave cues, the seat bucket and pan utilize eye-point correction so the seat can be used with a Heads Up Display (HUD) equipped aircraft simulator. This arrangement helps to maintain alignment with pilot and flight controls.

Like the seat pan's independent motion, the seat back has independent motions in surge and sway. Surge motion provides cues for longitudinal acceleration while sway motion applies pressure to the trainee's back to emulate lateral acceleration.

Simultaneous combinations of seat axis movement are used to generate cues. This feature allows the five controlled axes to produce cues in six degrees of freedom. For example, seat pan and seat back are simultaneously moved to produce pitch cues.

In addition to the seat pan and back motion, ancillary effects are generated by active seat harness control and by coupling the dynamic motion seat to a G-suit system. Seat harness control will tighten or loosen seat harness straps correlated to seat motion and to emulate the seat harness inertia reel. A G-suit system will inflate a trainee's anti-G-pants and vest in accordance with the aircraft model G-loading, which is simultaneously driving the seat motion. The physically induced seat motions are sometimes combined with a sound transducer which significantly extends the high vibration frequency range of the seat.

The current state of multi-axis technology enables tailoring of dynamic motion seats to the specific application in which they are installed. For example, locomotive simulators may only require three-axis seats while fast mover aircraft trainers require a seat that utilizes all axes. Seat size isn't dramatically impacted by the number of drive axes.

APPLICATION AND EVALUATION OF MOTION SEATS IN VARIOUS TRAINING ENVIRONMENTS

Motion seats have been installed in a variety of simulators, and studies have been conducted to evaluate their effect on training tasks. Review of these studies needs to focus on several pertinent topics. First, the study seat's technology has to be understood. Some of the seats in the studies provide cues in only a single axis. Other studies use multi-axis seats of varying fidelity. Second, it has to be determined whether the evaluation of the seat was performed over all of the training tasks applicable to that trainer, or was the evaluation limited to those tasks where the G-seat performs optimally. Finally, the integration of the seat into the trainer needs to be assessed. This ensures that the seat cues are properly correlated with the aerodynamic flight model.

Early studies revealed limitations of a single axis pneumatic G-seat and highlighted the need to address additional motion cues. The early NASA study on transport aircraft training using a single axis G-seat to augment platform motion showed only marginal training improvement (Parrish and Steinmetz 1983). This study only evaluated the seat cues for approach, landing flare and touchdown training tasks.

An evaluation of air-to-air combat training using a single axis seat showed improvement on tasks which utilized the same axis of motion as the seat. However, the study also showed no improvement on tasks utilizing other axes of motion (Ashworth, McKissick 1984). Additionally, the presence of vertical seat motion in this study seemed to sensitize the pilot to the absence of related cues when performing dynamic tasks, such as lateral and longitudinal motion cues.

Because of the implementation difficulties of the early G-seats, wide implementation of G-seats in simulation did not occur.

The first electrically driven multi-axis dynamic motion seats were developed for rotary wing trainers. Fixed wing applications followed after the multi-axis seat demonstrated success in the rotary wing training environment.

Rotary wing operations occur in a high dynamic environment in which the pilot experiences a variety of kinesthetic and haptic cues. By including such cues, the following types of training tasks can be provided: hovering in / out of ground effect, translational lift, loss of tail rotor authority, G-loading maneuvers and malfunctions to include main rotor out of track, main rotor out of balance and main rotor blade delamination. The motion cues help pilots recognize the characteristics of the maneuvers and are fundamental for effective control of the aircraft. Therefore, the addition of a dynamic motion seat can increase the number of training tasks that can be accomplished and improve the effectiveness of training tasks that are performed in non-motion equipped trainers.

The evaluation of these multi-axis dynamic motion seats in this environment was very favorable. In a study performed with a multi-axis dynamic cueing seat in a helicopter trainer, subjective pilot ratings and comments indicated that the addition of multi-axis dynamic motion seats to fixed base rotary wing training devices produced significant improvements in simulation realism, provided a more realistic pilot workload, and improved pilot acceptability (Grieg 1996).

Grieg's study (1996) highlighted that these first dynamic motion seats lacked the capability to provide adequate cueing in the yaw axis. This became apparent when performing certain tasks such as loss of tail rotor malfunctions that require the presence of strong yaw cueing. This deficiency prompted a redesign of the motion seat to account for added yaw cueing. ACME Worldwide Enterprises conducted an informal study in 2007 using USAF pilots that compared dynamic motion seats with and without an additional seat yaw axis to verify that the design modification improves yaw and roll cueing. The results of this subjective study showed a marked improvement on the perceived roll and yaw cueing felt by the pilots with the additional seat yaw axis. This increase in perception led to an increased acceptance that the dynamic motion seat provides the motion cues needed for the loss of tail rotor malfunction.

Further studies of the effect of dynamic motion seats on training tasks in a rotary wing environment were undertaken by a variety of groups (Chung, Perry 2001, Giovannetti 2002, Miller, Kocher 2009) with generally positive results. Positively impacted training tasks included bob up/bob down, hover, pirouette, and vertical landing. Other users report that the seats are particularly effective in replicating helicopter malfunctions like blade out of track.

The modern dynamic motion seats were also installed in commercial aviation simulators for evaluation (Burki-Cohen and Sparko 2007, Burki-Cohen, Sparko and Jo 2009). The goal of these studies was to document whether dynamic motion seats could be used in place of motion platforms, thereby improving training cost effectiveness. Again, the study results showed that seats in place of motion platforms provide motion onset cues that improve the trainee's perception of trainer realism for many tasks.

AN EVALUATION OF A MULTI-AXIS DYNAMIC MOTION SEAT IN THE AIR-TO-AIR COMBAT ENVIRONMENT

Because of the positive results of multi-axis dynamic motion seats in the rotary wing environment and fixed wing environments, an Air Force Research Laboratory (AFRL) study was conducted to subjectively and objectively assess the impact of a five-axis dynamic motion seat with harness belt tightening on the fidelity and training capabilities of two F-16 simulators in an air-to-air combat training environment. A five axis seat was installed in a low-fidelity Deployable Tactical Trainer (DTT) and a high-fidelity Mobile Modular Display for Advanced Research and Training (DART). Figure 2 shows the seat in the DTT during evaluation.

Figure 2 AFRL DTT with dynamic motion Seat

In fall 2009, 12 F-16 pilots (all instructor pilots) flew a variety of tactical 1-ship maneuvers and 2-ship missions in the DTTs. Study tasks were balanced and randomized using a within-subjects design so that each pilot flew all tasks with and without the dynamic seat (only one DTT had the seat installed). Similarly, in spring 2010 the study was replicated in the DART using 12 new pilots (10 of 12 were instructor pilots). Objective performance data was collected during both studies and is currently being analyzed to determine the quantitative impact of the dynamic motion seat on pilot performance. Surveys were administered to assess the perceived training capabilities of the simulators (with and without the dynamic seat) and to assess the perceived impact of and general reactions to the dynamic motion seat.

The perceived training capability of each simulator (DTT and DART) with and without the dynamic motion seat was assessed using a fidelity survey instrument (Schreiber, Bennett & Gehr, 2006). For each F-16 mission essential competency (MEC) experience (Colegrove & Alliger, 2002) and emergency procedure (EP), participants rated the extent to which they were able to gain the experience in the simulator. The rating scale ranged from 1 (capability exists but is very poor) to 5 (capability exists and is very good). A rating of 0 (can't experience at all) was also an option.

Combining training capability rating results from the DTT and DART studies, the dynamic motion seat was shown to significantly improve the training capability for 12 of the 70 air-to-ground (A/G) experiences, 4 of the 55 suppression of enemy air defense (SEAD) experiences, 2 of the 44 air-to-air (A/A) experiences, and 1 of the 27 EPs.

As a more sensitive measure, participants also rated the impact of the motion seat on each MEC experience and EP. The rating scale ranged from -2 (very detrimental) through +2 (very beneficial).

Combining impact rating results from the DTT and DART studies, the dynamic motion seat was shown to have a consistent beneficial impact across the experiences. The dynamic seat was not rated as having a detrimental impact for any of the MEC experiences or EPs. The ratings showed a statistically significant beneficial impact for 29 of the 70 A/G experiences, 12 of the 55 SEAD experiences, 21 of the 44 A/A experiences, and 8 of the 27 EPs.

In responses to open-ended questions on the survey, pilots reported improved energy management, pitch awareness, roll awareness, airspeed awareness and decreased need to monitor the G-meter as the most beneficial training aspects of the dynamic motion seat. These results are consistent with pilot ratings of the impact of the dynamic motion seat on various flight phases. Pitch and roll awareness, G-onset, continuous G-monitoring, and energy management all received average ratings greater than 4 on a scale of 5 and were statistically significant.

Although pilot perceptions of simulator training capabilities and of the impact of the dynamic seat are important, it is more important to show the resulting impact on performance. Objective performance data is currenly being analyzed to examine the effects of the dynamic seat on the dynamics of flight maneuvering, e.g., energy management, pitch, roll, and G awereness.

DYNAMIC MOTION SEAT INTEGRATION

The dynamic motion seat offers a compact package that closely fits the envelope of the vehicle seat itself. The tight packaging offered by the motor technology permits the dynamic motion seat to be retrofitted quite easily into existing simulators and new designs.

The mechanical envelope is normally the first criteria evaluated when considering a dynamic motion seat, but it is certainly not the only criteria. The software interface can just as easily dictate the level of difficulty and cost. It is therefore important to evaluate the level of effort needed to integrate a dynamic motion seat. The electrical interface must be adaptable to the simulator power design, whether it is a new or existing design. The low power requirements of most dynamic motion seats lend themselves well to electrical requirements. The elimination of pneumatic and hydraulic requirements of the current dynamic motion seats makes the integration tasks that much easier.

The dynamic motion seat, in most cases, will fit within the existing seat envelope whether the simulator is for a fixed wing aircraft, rotary wing aircraft, ground vehicle or water craft. The small size of the motors and actuators permits engineers to fit the technology into a small footprint. However, the effort to accomplish this design task is no small feat, and the value of experience should not be overlooked. The seats normally provide the same adjustments that are found in the vehicle seats, such as electrical adjustments and slide rails. The designs can be adapted to fit simulator specific design requirements so seats can slide farther aft for specific ingress/egress needs.

The software interface is perhaps the most closely correlated to integration cost and complexity. This is due to the requirement to provide the data to drive the dynamic motion seat properly and to provide the correct cueing effects to the trainee. A seat that requires the developer or integrator to derive and implement the motion equations is normally a high risk and high cost approach. This approach requires experience and familiarity with the device to accomplish this task successfully. A much lower risk and cost approach is to utilize a dynamic motion seat that has the motion algorithms integrated as part of the seat itself. This approach leaves the translation of the vehicle motion into seat cueing to the manufacturer's experts and the integrator simply provides vehicle acceleration and velocity data that is readily available.

Using a dynamic motion seat in a simulator is not a panacea for poor dynamic software model fidelity; a dynamic motion seat will not improve a low fidelity dynamic model. In fact, the reverse is true. Because of the fast seat response, the seat magnifies any inconsistencies of the dynamic model. Improperly modeled aerodynamic and engine effects, like torque spikes or ground interaction errors that are not noticed in a visual scene, will be more obvious with a dynamic motion seat. Seat performance will only be as good as the host dynamic model. It is important to ensure the dynamic motion seat has the tools required for smooth integration of these effects.

CONCLUSION

Dynamic motion seats currently on the market are a far cry from the early pneumatically driven G-seats developed in the 1970s. The modern dynamic motion seats use small, powerful, precision controlled motors as the motive force to provide cues in up to five separate axes. These seat cues, when combined with ancillary cues, such as an active harness or a G-suit, provide an immersive haptic environment for the trainee.

The results from studies using multi-axis dynamic motions seats show positive impact to a wide variety of training tasks. The cues provided by the seats improve the trainee acceptance of the trainer.

Current technology enables modern multi-axis dynamic motions seats to fit easily within even the smallest aircraft cockpit. Additionally, the seats are currently available as an integrated subsystem facilitating integration of the seat into the trainer. These features, coupled with low initial and recurring costs, make the current version of the dynamic motion seats very attractive.

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