Dynamic Flight Simulator for Enhanced Pilot Training
SAFE Europe (March 2002)

B. Levin, D.Kiefer

Britta Levin is a research officer at the
Swedish Defense Research Agency, Linköping, Sweden
(telephone: +46 13 378536, e-mail: britta.levin @foi.se).
Dennis Kiefer, is a simulation engineer with
Wyle Laboratories, El Segundo, CA 90245-4100 USA
(telephone: +1 215 353-7219, e-mail: dkiefer@wylelabs. com).

***Abstract*-- In 1994 the Swedish Air Force decided that extended manned centrifuge capabilities were needed in order to meet future requirements and training needs. The Swedish Defence Materiel Administration (FMV) was assigned to initialize acquisition of a Dynamic Flight Simulator (DFS). In 1996 a contract for delivery of a DFS was awarded to Wyle Laboratories in El Segundo California USA.**

The DFS is a versatile high performance pilot training and research device. Technically it is a man-rated centrifuge combined with fully controlled and motor operated pitch and roll gimbals (2-axis) and a flight simulation system based on JAS 39 aircraft models and controls. A unique perception algorithm modeling the expected sensations provides a "realistic" flight experience and increased comfort since undesired sensations are minimized.

A variety of operation modes allow traditional centrifuge training as well as extended or applied G-training. In applied G-training the pilot being in full control of a realistic environment is given meaningful tasks leading to more effective G-training.

The DFS is currently in the final stage of on-site testing and beginning of man-rating. It is expected to be ready for training in the fall of 2002.

I. INTRODUCTION

Fig. 1. The Swedish DFS in Linköping

Sweden has a long experience of human centrifuge applications. The human centrifuge at the Karolinska Institutet has been operational since the middle of 1950s.

In 1993 the Swedish Air Force realized that extended manned centrifuge capabilities were needed in order to meet the Gripen, JAS 39, performance and future training needs. A decision was made to upgrade the centrifuge at the Karolinska Institutet and to acquire a DFS to be located in Linköping.

The Swedish Defense Materiel Administration (FMV) was assigned to initialize acquisition of a Dynamic Flight Simulator (DFS). The Request For Proposal was sent issued in 1994. The procurement involved evaluation of several existing DFS/centrifuges. The contract was awarded to Wyle Laboratories in El Segundo CA USA, on Sept 1 1996.

The DFS was delivered on-site Feb 2000 and is currently in the final stage of acceptance testing and beginning of man-rating. Expected to be operationally ready for training in late 2002.

II. FUNDAMENTALS OF DYNAMIC FLIGHT SIMULATION

Dynamic flight simulation can be described simply as a flight simulator that uses a human centrifuge as its motion base. DFS requirements arise out of a need to train high performance aircraft pilots to perform more effectively as they execute their flight missions and also from a need to study the human responses to acceleration with possible methods to increase pilot safety and effectiveness.

The DFS device then must be able to recreate the acceleration time histories that occur in flight and also provide the perception of flight motion so that training can be effective and so that research is applicable to the actual flight environment. Since the acceleration time histories include sustained acceleration, the DFS motion base must be a centrifuge with a reasonably large radius arm in order to minimize the disorienting effects of angular accelerations on the pilot vestibular system.

Time history requirements also mandate using a two-axis controllable gimbal system to support the gondola containing the DFS simulated cockpit, the pilot and the various simulator support systems. An important, perhaps non-obvious, feature is that the pitch axis, defined with the pilot facing tangential to the arm motion, must be supported within the roll axis gimbal. This allows the DFS to respond quickly to changes in the commanded linear acceleration vector. Finally, there must be a configurable control algorithm that can allow the DFS to be used to give the pilot the perception of flight or to give a researcher the ability to command accurate acceleration time histories in all axes.

A. Definition:

A DFS must have the following characteristics:

- Large radius responsive centrifuge
- Simulated cockpit within a gondola
- Gondola supported by a two axis controllable gimbal system with the pitch axis innermost
- Special DFS configurable perceptual control algorithm

B. History

There has long been an interest in using a centrifuge as a flight simulator. Table 1 shows some of the early implementations. Early approaches before 1980 relied on techniques that solely attempted to match the G-vector between the simulated aircraft and the centrifuge. A pioneering technological breakthrough was made by Crosbie [3] in the F14 DFS at Warminster, which used a new method of perceptual control.

TABLE 1
DFS HISTORY – IMPLEMENTATIONS

Date	A/C Type	Control	Comment
1955	X-15	G Vector	US Navy-Warminster
1965	Boeing 707	G Vector	Clear Air Turbulence
1970-75	F4	G Vector	US Navy - Warminster
1983-87	F14	Perceptual	US Navy, 3Gz/s, Flat Spin
1989	Generic	Perceptual	ACES 13 G/s, High
1992	Generic	Perceptual	10 G/s, Multi-purpose, Light-Wt
1994	F-18	Perceptual	6 G/s, Full Mission
1996	F-22	Perceptual	Full Mission
2002	JAS 39	Perceptual	Swedish Air Force, Full Mission

C. Centrifuge Control Algorithm

As in every motion-base flight simulator, aircraft motions are transformed using a special control compensator into centrifuge motions that the DFS pilot feels. There are three steps to this transformation. 1) The centrifuge arm accelerates to generate a mapped G magnitude and the gimbals orient the resulting G vector angle to that of the simulated aircraft; 2) A *cross-sensory matching* linear acceleration vector time history is added to cancel out undesired sensations of motion; and 3) Aircraft angular accelerations are washed out and added to the DFS motion. The cross-sensory matching concept in step 2 is the key to using the centrifuge as a flight simulator. It is the concept developed by Crosbie in the early 1980's and improved by Wyle Laboratories. This perceptual control algorithm is tuned using human perceptual models of both the simulated aircraft pilot and the DFS pilot.

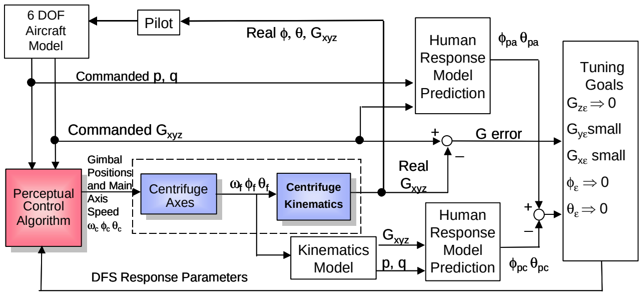

Fig. 2. The compensation process is optimized using human response models of both the simulated aircraft pilot and the DFS pilot. These models were experimentally derived using data collected on the US Navy DFS in Warminster, PA.

D. Control Characteristics

There are several other operationally significant characteristics of a DFS that affect how it is used.

1) Aircraft to Centrifuge Acceleration Mapping

There is a function, which maps Gz of the aircraft into the Gz of that is felt by the DFS pilot as shown in figure 3.

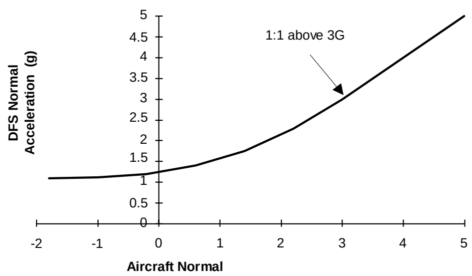

Fig. 3. Aircraft Gz is mapped into DFS Gz with a smooth nonlinear mapping which provides a 1.0 aircraft Gz trim point when the DFS motion base is typically at 1.5 Gz. The pilot adapts quickly to this new trim acceleration. It allows some pushover effect when the pilot moves the stick forward.

2) Control Optimizations

The DFS has control options that allow a) Emulation of a swinging carriage type centrifuge; b) Acceleration vector matching between aircraft commands and DFS response and c) Perceptual matching to give the best pilot sensation of flight.

3) Open Loop vs. Closed Loop Operation

The DFS can be used either in an open loop with pre-programmed acceleration profiles or with the pilot in control of a flight simulation which drives the centrifuge.

III. Technical Data

The Dynamic Flight Simulator (DFS) is a high performance training and research device that combines a man-rated centrifuge with fully controlled and motor operated pitch and roll gimbals and a flight simulation system.
The structural fatigue life > 40 years

A. Performance comparison

Table 2
Performance-comparison

Performance	Karolinska Institutet	DFS Linköping	Brooks San Antonio TX
Gz onset rate	6.0	10	6.0
Axis	single	two	single
Application	-----	flight sim	g-track mode
Max Gz	15	15	15

B. DFS machine components

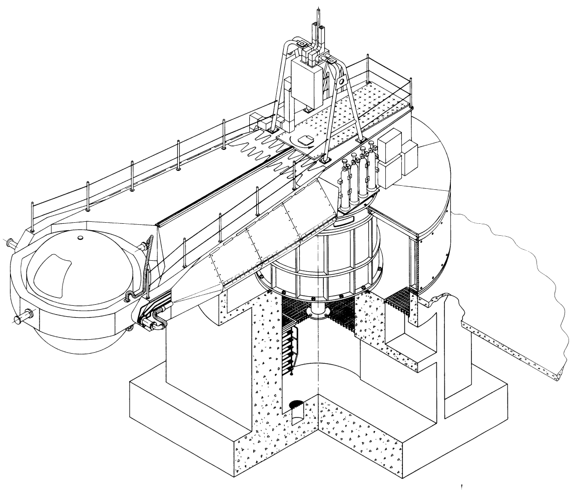

Fig.4. DFS machine

- Schweizer Aircraft, New York delivers the arm and gondola caps. Arm Length: 9.14 m, Weight: 30 tons. Gondola diameter: 2.7 m
- The main drive is a DC current motor delivered by Westinghouse, Texas. Weight: 93 tons
  Max current: 9145 Amps at 750 Volt DC, Rated speed: 41 rpm, Power requirement: 11 kV
- The roll drive is an AC motor delivered by Reliance Electric, Virginia
  Max roll acceleration 15 rad/ s^2
- The pitch drive is DC Servo motor from Kolmorgen, US. Max pitch acceleration 20 rad/ s^2
- The DFS is also furnished with a 48 channel Data Acquisition System and capabilities for medical supervision.

C. Gondola systems

The gondola consists of permanent systems and configurable inserts. The training insert, a Gripen cockpit mock-up, can accommodate positioning of subject heart- or head level in the center of gondola. A separate insert for acceleration research is a turnable seat, which can be rotated or tilted in various angles.

D. Flight simulation system

Fig. 5. Training insert

The flight simulation capabilities are based on:

- JAS 39 Cockpit mock-up containing real Aircraft hardware such as MB-seat, stick, throttle and Oxygen regulator
- Aerodynamic model delivered by Saab (ARES). Current setup contains one weapon load, no fuel system simulation or ground handling
- Head-up and head down display instrumentation. Head down software is a derivative of Saab glass cockpit (virtual front panel) from 1997. The software contains basic avionics- and weapon system functionality such as simplified IR and Radar modes and a choice of gun of missile
- Visual out-the-window displays consisting of 3 monitors with a total field-of-view of approximately 90 degrees. The database is in Open Flight format and shows an area around Oakland CA

E. Instructor operator station

Fig. 6. Instructor Operator Station

The DFS is equipped with an Instructor Operator Station (IOS) providing:

- Scenario creation and control
- Targets, air and surface performing:
    - waypoint flight
    - intelligent threats
    - various skill levels
    - weapon loads
- Cockpit repeater of HUD, OTW and HDD display
- A separate IOS joystick for mission preview

F. Simulation quality

The flight simulation objective is to provide a ”JAS 39-like” environment with respect to A/C dynamics, high-g maneuvering and cockpit layout. It is not necessary to provide a complete or detailed simulation of all JAS 39 subsystems nor to facilitate the training thereof.

IV. Field of Application

The DFS has been developed for a wide field of applications such as:

- Pilot training and qualification
- Screening of pilot applicants
- Medical evaluation
- Research in Flight physiology
- Research in Man-Machine Interaction
- Development and testing of life-support & Aircraft equipment

V. Enhanced Pilot Training

Enhanced or applied pilot acceleration training is the next step beyond the traditional training in use today. The DFS offers the possibility of a new more comprehensive training experience with better mission consistency and hopefully with improved pilot acceptance. The Swedish Air Force has many advantages now in reaching this goal. The smaller pilot population and the availability of the DFS are two advantages not enjoyed during the development of the existing training curriculum. These circumstances allow the possibility of the enhancements that are described here.

Recent analysis of US G-LOC incidents has suggested that improvements to the existing acceleration training may be valuable. The DFS offers a more aircraft real environment to support such changes [1].

A. Pilot Free Flight Task

With this task pilots coordinate vehicle control with their anti-G-straining-maneuver in a natural and therefore relevant way. The instructor-guided curriculum appropriate to the specific aircraft type can be implemented.

B. Target Chasing Task

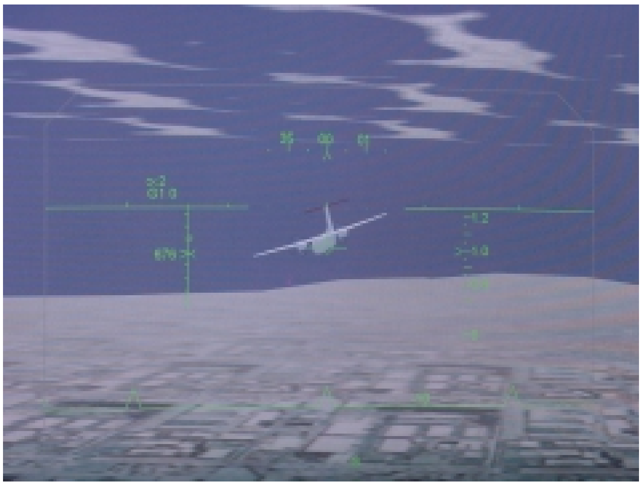

Fig. 7. Target chase

The target-chasing task is a prerecorded free flight that is played back through the DFS out-the-window display system to provide the pilot with a target to chase. The target is initially placed at a user-defined distance in front of the ownship and when released the pilot tracks the target according to goals determined by the instructor. A wide variety of scoring variables are available for inclusion in any desired curriculum.

C. “G” Tracking Task

The “G” tracking task is a three-dimensional piloting task instead of the traditional “G-Stick” single axis tracking used with many existing acceleration training programs. The DFS flight simulation environment gives targeting cues that lead the pilot into following a prescribed acceleration profile.

D. *Mission Relevant Approach*

This is a broad approach to acceleration training. It can involve more mission related events and tasks which provide realistic mental stress along with the physical stress of the acceleration. The potential of this task is limited only by the imagination of the developer.

VI. Future Applications

Many potentially available DFS training and research applications are technically feasible for the device but need to be programmatically developed before they can be considered useful. This process includes defining specific training goals, creating associated specific environmental conditions and validating the effectiveness of the program. The DFS is the key enabling technology for the implementation of these possibilities.

A. *Push-Pull Implementation*

It is well documented that a less than one Gz (Push) exposure can reduce the acceleration tolerance of the pilot to subsequent greater positive Gz exposures (Pull). The DFS can be enhanced to provide these Push-Pull acceleration exposures to the pilot. The general approach is diagrammed in figure 8. This approach has been successfully used for research purposes.

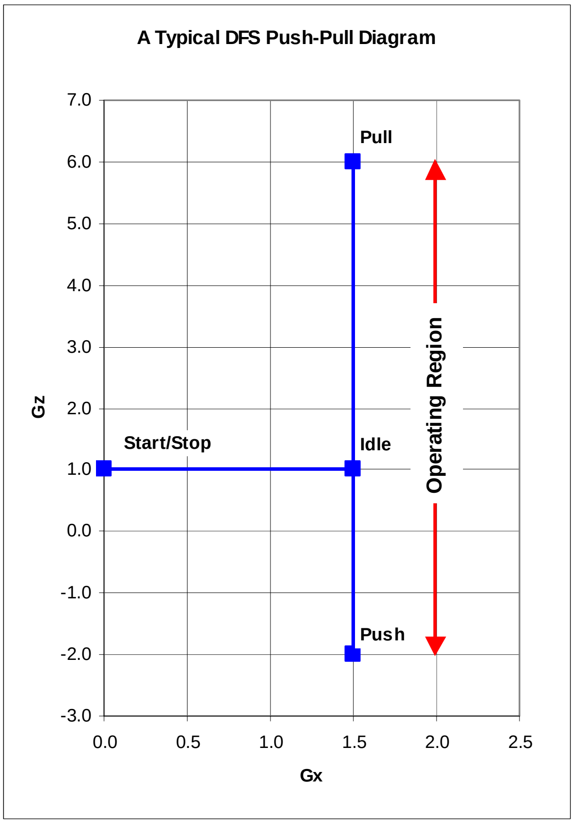

Fig. 8. This push-pull diagram depicts the compromise that every ground based trainer must satisfy implementing sustained low Gz (<1.0) followed by sustained high Gz (>1.0) in that in the presence of the earth's gravity the unit sphere below 1.0 Gz is unavailable. The Wyle DFS implementation allows constraint of the nominal Gx value to be a user selectable constant, in this case 1.5.

B. *Training at the Edge of the Flight Envelope*

The DFS can be used to recreate the dynamic environment associated with abnormal or extreme flight conditions that would be dangerous to experience in the aircraft itself. Examples of such conditions include flat spins, dynamic departures, and other such phenomena including certain aircraft system failures.

C. *Spatial Disorientation and Situational Awareness*

The DFS can be used to provide vestibular stimuli that can result in the pilot becoming disoriented in the aircraft. Availability of realistic cockpit and task loading can create the acute effects of acceleration such as the "Almost Loss of Consciousness Syndrome"[4] and physiological fatigue. Potentially trainable situational awareness conditions are possible.

D. *Tactics*

It may be valuable to develop or train for certain offensive or defensive tactics where acceleration is a significant factor of proper execution. Maneuvers such as surface to air missile avoidance or some types of air combat maneuvers are possible to execute in the DFS.

E. *Cockpit Design Evaluation*

Human factors is becoming even more important in Aircraft Cockpit design with the increasing complexity in the pilot environment and the vast amount of available information. The DFS offers a flexible environment for evaluation of new concepts, prototyping of new A/C software and equipment design.

VII. References

[1] Live Fire Testing and Training Program, Operational Test and Evaluation / Live Fire Test, Office of the Secretary of Defense, *Report of Aircrew Experience with G Induced Loss of Consciousness: Problem Identification Analysis*, June 2000.

[2] T.J. Lyons (Chairman), W. Albery, R.D. Banks, W. Bles, G. Calhoun, J.-M. Clere, J.-L. Firth, J.-Y. Grau, F. Knox, P. Le Blaye, J. Linder, J. Plaga, V. Ponomarenko, V. Santi, L. Specker, M. Stucky, W.C.M. Tielemans, H. Welsch, *Human Consequences of Agile Aircraft*, NATO-RTO-TR-015, AC/323(HFM-015)TP/15, May 2001.

[3] R.J. Crosbie, *Application of Experimentally Derived Pilot Perceptual Angular Response Transfer Functions*, AIAA-83-1100-CP, AIAA Flight Simulations Technologies Conference and Technical Display, June 1983.

[4] K.L.Morrisette D.G. McGowan, *Further Support for the Concept of a G-LOC Syndrome: A Survey of Military High-Performance Aviators*, ASEM Journal 2000.

[5] J.E. Whinnery, A.M.Whinnery, *Acceleration Induced Loss of Consciousness*, v. 47 Archives of Neurology, July, 1990