FLIGHT SIMULATION TECHNIQUES WITH EMPHASIS ON THE GENERATION OF HIGH FIDELITY 6 DOF MOTION CUES

ICAS-86-5.3.3

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Abstract

The current status of flight simulation technology has reached the level, where the aircraft dynamics can be simulated with the fidelity, required for 'Total Simulation' in civil air crew training. In the first part of this paper the main systems of a piloted flight simulator will be discussed:

* The real-time digital computer system, driving the simulator.
* The simulator cockpit, providing various levels of equipment fidelity to the pilot.
* Visual systems, where improved display devices should take advantage of improvements in CGI-systems.
* Motion systems, generating aircraft like specific forces and angular accelerations.

Special emphasis will be placed on a unique method to generate high fidelity six-degrees-of-freedom (6 DOF) motion cues in the second part of the paper. Time responses of the specific forces and angular accelerations generated in the aircraft cockpit will be compared to the same quantities generated in the simulator cockpit on top of a 6 DOF motion system. The control surface inputs, generating these time responses, result from so called 'Flight Simulator Critical Manoeuvres'.

I. Introduction

From the humble beginnings of flight simulation Back in 1930 with the bellow-driven 'Link'-trainer, to today's multi-million dollar flight simulators, dramatic advances have been made in the research and application of flight simulation techniques. Subjective fidelity, or a sense of realism, in the flight simulator is essential to productive use in the subsequent four main areas of flight simulator applications:

- flight crew training
- research on the man-machine interface
- aircraft design and development
- certification and accident investigations

To create subjective fidelity, varying degrees of engineering similarity to the actual flight situation are required, depending on the task and the objectives of the simulator application. Dynamic mathematical models of the aircraft's aerodynamics and inertia characteristics can now be realized to represent actual aircraft in flight characteristics. Cockpit displays and controls can be faithfully duplicated. However, in two main areas of aircraft-state feedback to the pilot, the ground-based flight simulator can never actually duplicate the aircraft's behaviour in flight. These are the generation of:

a. the visual scenery of the outside world;
b. the simulator cockpit motion.

As a consequence an engineering compromise for visual and motion cueing is inevitable.

At the Department of Aerospace Engineering of Delft University of Technology (DUT) flight simulation activities started in 1955 and since 1969 the disciplinary group for Stability and

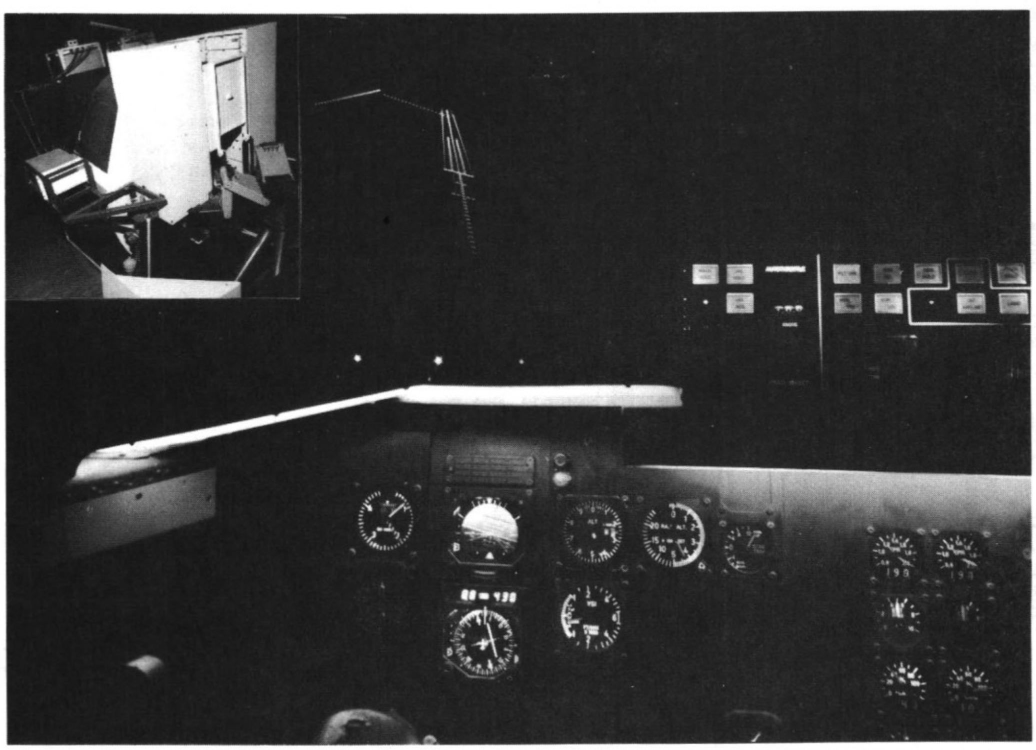

Fig. 1: Delft University moving-base visual flight simulator.

Control of this department operates a moving-base visual flight simulator, see Fig. 1.
This flight simulator is used in various research programs and one of the topics is the research and application of the techniques of flight simulation.
In Section II of the present paper, the four principal parts of the flight simulator will be discussed, i.e.:

1. the real-time digital computer;
2. the flight simulator cockpit;
3. the visual display system;
4. the cockpit motion system.

The requirements to be put upon these systems, relative to the Advisory Circular of the Federal Aviation Administration in the USA [2], will be presented.
In Section III special emphasis will be placed on a unique method to generate high fidelity six-degrees-of-freedom (6 DOF) motion cues. Time responses of the specific forces and angular accelerations generated in the aircraft cockpit will be compared to the same quantities generated in the simulator cockpit on top of a 6 DOF motion system. The control surface inputs, generating these time responses, result from so-called 'Flight Simulator Critical Manoeuvres'.
The paper will be restricted to mainly civil applications of flight simulation.

II. Main systems of a piloted flight simulator

II.1. General

The basis of any flight simulator is the mathematical model [3] including the data package [4] describing the characteristic features of the airplane to be simulated. No matter how sophisticated the systems of a flight simulator may be, an incorrect or incomplete mathematical model and/or data package will cause the simulator to be unable of fulfilling its purpose satisfactorily.
The advantages of ground-based simulators over airborne flight operations include reduced cost, fuel savings, safety, no pollution and noise, and more efficient training. Research and development areas where simulators play a vital role include:

PHASE I : TRAINING + PROFICIENCY CHECKS:

* TAKE-OFF AND LANDING
* GROUND HANDLING

PHASE II : UPGRADE F/O TO CAPTAIN
TRANSITION FROM ACT-TYPE

PHASE III: TOTAL SIMULATION

REQUIREMENTS:

	VISUAL	MOTION	LATENCY
PHASE I	NIGHT/DUSK FOV 48°/30°	3 DOF	300 MSEC
PHASE II	DUSK + TEXTURE FOV 75°/30°	6 DOF	150 MSEC
PHASE III	DAY/DUSK/NIGHT FOV 75°/30°	6 DOF	150 MSEC

Table 1: FAA Advanced Simulation Plan.

investigation and improvement of the handling characteristics of new aircraft, practice of emergency procedures and manoeuvres which can be hazardous if conducted in the air, pilot capabilities and workload, evaluation of new display and control systems, flight procedures for possible reconfiguration of the air traffic control system, and certification and accident investigations.
For the use of flight simulators for flight crew training, the US Federal Aviation Administration (FAA) has issued its Advanced Simulation Plan [2]. The allowances and requirements of Phase I, II and III simulators are summarized in Table 1.
Most of the training simulators acquired these days are phase II approved. This means that a pilot could graduate from one type of aircraft to another or upgrade from first officer to captain with total training on the simulator.
In the next subsections the main flight simulator systems will be discussed, starting with perhaps the most important part, i.e. the 'real-time' digital computer system driving the simulator.

II.2. Real-time digital computer system

Flight simulation is realized by mathematical modeling of the aircraft's aerodynamic, aeroelastic, flight control, propulsion, landing gear, avionics and environmental characteristics like the response to atmospheric turbulence and wind shear, see Fig. 2.
Mathematical models, used to simulate modern aircraft, consist of an extensive set of nonlinear differential equations with large amounts of aerodynamic function data (tables), sometimes depending on 4 or 5 variables, arbitrary discrete and continuous forcing functions, and a multiplicity of constraints imposed on the states of the different aircraft systems.
From the resulting forces and moments, generated by these systems, the equations of motion are composed and solved by the digital computer using an adequate integration algorithm. This allows the simulation of the complete range of static and dynamic aircraft operating conditions, including landing and take-off, ground-handling, emergency situations such as engine failure, stalls and component malfunction. For training simulators other significant parts of the computations involve fuel system equations, weight, balance and inertia changes, autopilot/ flight director functions, flight management system, navigation functions and radio aids.
Aeronautical radio, Inc. (ARINC) has prepared a working paper [5] for the Airlines Electronic Engineering Committee (AEEC) to achieve direct use of applicable airborne equipment in flight simulators, providing for readily available spares, the most recent version of operational software, and the assurance that equipment response will be the same in the aircraft and simulator. In particular the integration of 'the seventeen IATA Simulator Functions' (freeze, set, slew, recall, etc.) in new avionics designs is proposed [5]. Because of the presence of the PILOT-IN-THE-LOOP, and/or hardware and avionics in the loop, the complete set of equations must be solved in real-time. This means that the simulated events must occur in the same time scale as they would occur in the actual aircraft. The real-time contraint for a serial host computer, with digital and analog input-output, can be expressed as:

$$[\text{Code Processing Time} + \text{Input/Out Time}] < [\text{Sample Period}] \quad (1)$$

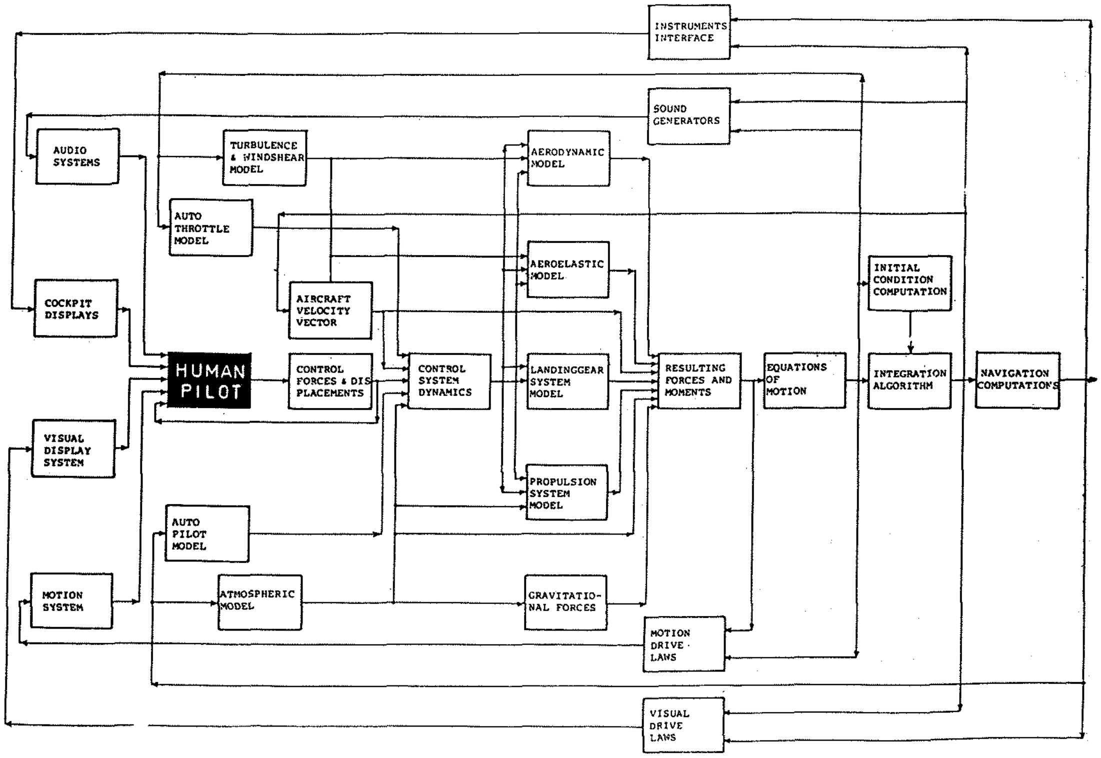

Fig. 2: Block diagram of software and hardware modules for piloted flight simulation.

This can place severe demands on available computer power. The computations needed for flight simulation can be broken down into the basic operations summarized in Table 2.

- FUNCTION GENERATION (UP TO 5 INDEPENDENT VARIABLES)
- ADDITION AND SUBTRACTION
- MULTIPLICATION AND DIVISION
- NUMERICAL INTEGRATION
- COORDINATE TRANSFORMATION
- ANALOG AND DISCRETE INPUT/OUTPUT
- BULK DATA ACCESS (NAV. DATA BASES)
- DECISIONS AND BRANDCHING (BOOLEAN)

THE REAL-TIME CONSTRAINT FOR A SERIAL PROCESSOR:

$|\text{CODE PROCESSING TIME} + \text{I/O TIME}| < |\text{SAMPLE PERIOD}|$

Table 2: Basic computational operations.

In real time flight simulation, the computer must carry out all calculations in the mathematical model, including input/output, a sufficient number of times per second to achieve dynamic fidelity of the highest natural frequency present in the simulation response [6]. Fig. 3 shows the required computational duty cycle (sample period) as a function of aircraft natural frequency.

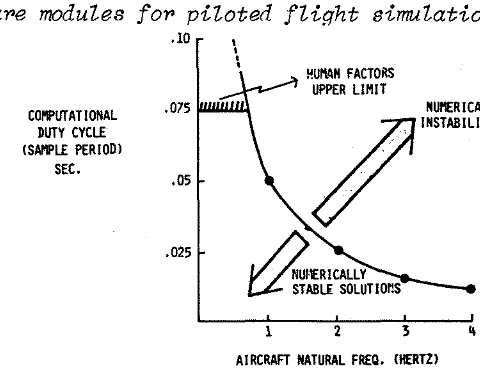

Fig. 3: Required sample period for real-time simulation of fixed wing non-aeroelastic aircraft [6].

For a particular application, e.g. the simulation of a Boeing 747, the real-time constraint (1), the total number of operations (N_o), the integration algorithm (P_s), the number of samples per cycle of the highest frequency of interest (S_c) and the operational frequency (F) determine the required simulation computer power, see Table 3.
For the 747 simulation this results roughly in a required computer power of 4.8 Million Floating Point Operation per second (MFLOPS). Table 4 shows some estimated computer requirements for different types of aircraft [6].
An alternative way to meet the high required computer power of todays modern flight simulators is the use of a distributed computing system [7]. It consists of microprocessors, partitioned on a functional basis with the autonomous major functions connected as a newtwork. In Fig. 4B the microprocessors, providing for the major functions in the functionally distributed computer system,

replace the host computer in the traditional simulator configuration in Fig. 4A.

NUMBER OF FLOATING POINT OPERATIONS PER SEC:

$$FLOPS = N_0 \cdot P_S \cdot S_C \cdot F$$

WHERE: N_0 - NORMALIZED STATIC OPERATIONS TO UPDATE DYNAMICS PER PROGRAM PASS ($\approx 4 \times 10^4$ FOR 747)

P_S - NUMBER OF PROGRAM PASSES PER SAMPLE OF INPUT DATA ($\approx$ 4 FOR 4 PT. RUNGE KUTTA)

S_C - NUMBER OF SAMPLES PER CYCLE OF HIGHEST NATURAL FREQUENCY ($\approx$ 20)

F - OPERATIONAL FREQUENCY (BANDWIDTH) IN HZ ($\approx$ 1.5)

COMPUTATION REQUIREMENT FOR 747-SIMULATION:

$$FLOPS \approx 4,8 \times 10^6 \approx 4,8 \text{ MFLOFS}$$

Table 3: Required simulation computer power.

AIRCRAFT TYPE	MFLOPS
CONVENTIONAL TRANSPORT	2,4-4,8
FIGHTER & WEAPONS	3-6
ROTORCRAFT (5 BLADES, 200 RPM)	14-15

Table 4: Estimated computer power for different simulations.

A typical functionally distributed computer system for an Airbus A300-600 simulator [7] may contain seven major functions with a total of 27 CPU's for its real-time application software.
At the Dept. of Aerospace Engineering of DUT a

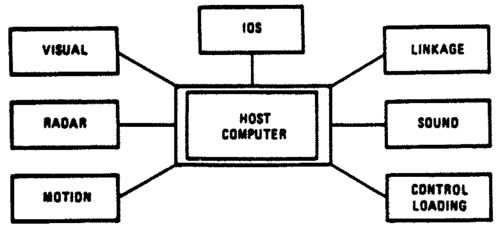

Fig. 4A: Traditional simulator configuration.

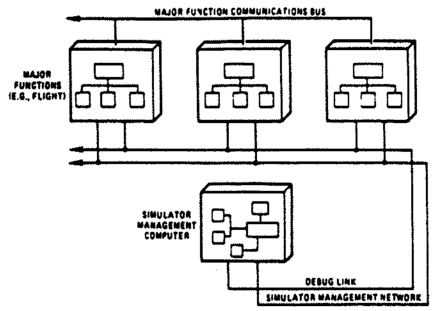

Fig. 4B: Functionally distributed simulation [7].

Gould SEL 32/87 is driving the moving-base visual flight simulator [1], replacing an EAI Pacer 600 hybrid computer system. The real-time simulation software, used in the system, has a modular program structure [8], as shown in Fig. 5.

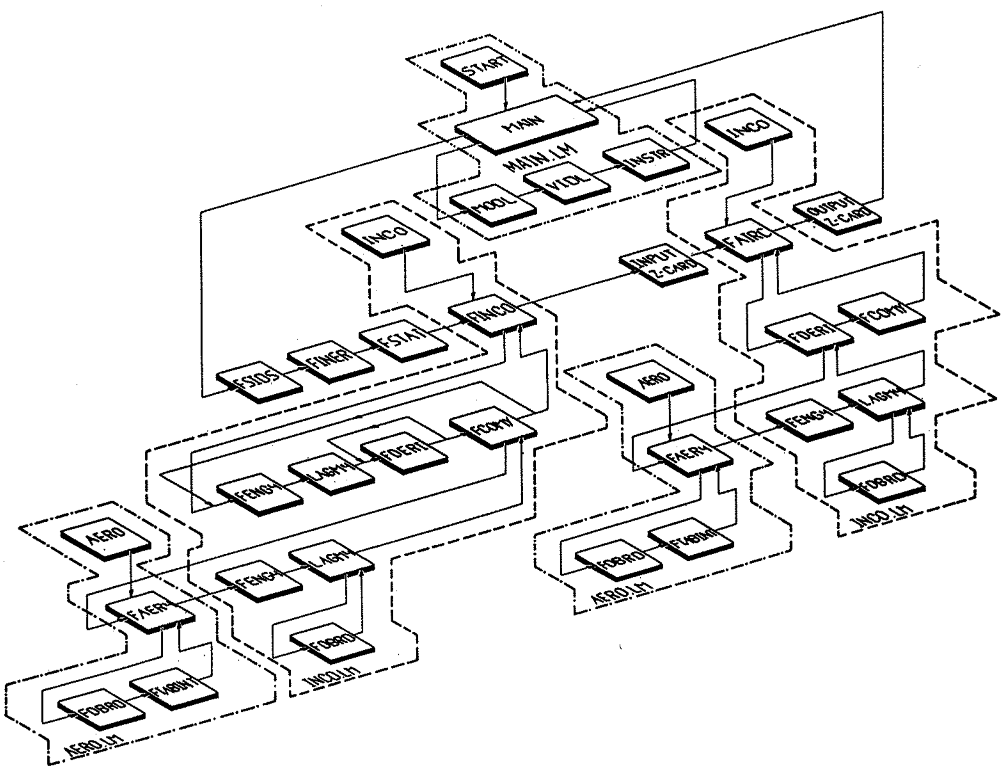

Fig. 5: Modular program structure of DUT real-time simulation software.

The acronymus used for the different modules are explained in the Appendix. This modular program has been developed on the Amdahl 470/V7 computer of the Delft University Computing Centre to reduce program development effort and cost. One of the applications is the (real-time) simulation of the flight dynamics of a large flexible aircraft in atmospheric turbulence [9].
FAA-phase I, II and III [2] computer requirements are presented in Table 5. The maximum latency, mentioned here, will be discussed in Section III.

• ACCURACY	32 BIT
• HIGHER ORDER LANGUAGE	FORTRAN (77, 8X) PASCAL ADA?
• EXTENSIVE SOFTWARE DIAGNOSTICS	
• SELFTEST CAPABILITY	
• MAXIMUM LATENCY:	
PHASE I	300 MSEC
PHASE II, III	150 MSEC

Table 5: FAA - Phase I, II and III computer requirements.

II.3. The flight simulator cockpit

Before starting the discussion on the flight simulator systems providing direct aircraft-state feedback to the pilot, it is appropriate to divide the cues these systems provide to the pilot into two classes [10]:

- Equipment cues providing a duplication of the appearance and feel of the flight displays and controller force and displacement characteristics inside the simulator cockpit.
- Environment cues providing the (attempted) duplication of the environment using visual out-of-the-window cues and platform motion cues.

Fidelity is expressed by the degree to which these equipment and environmental cues match those of the real aircraft. A subtle distinction between the real cues measured objectively and the cues the pilot subjectively experiences provide the following definitions for two types of fidelity [10]:

- Objective fidelity is the degree to which a simulator reproduces the behaviour of the real aircraft, in flight and on the ground, as sensed and recorded objectively by an instrumentation system on board the aircraft and the simulator, respectively. By including both equipment and environmental cues, this definition can encompass all pertinent dynamic cue timing and synchronization aspects of simulator fidelity.
- Perceptual fidelity is the degree to which the pilot subjectively perceives the simulator to reproduce the real aircraft behavior in the operational task situation. The consideration of the operational equipment in the context of the task situation ensures that not only cue timing and synchronization, but also cue priority effects in the way the pilot performs his task, are taken into account.

The requirements for objective fidelity in the cockpit of the flight simulator vary with its objectives. However, the general assertion can be made that the character and workload of the pilot's task in the simulator should be representative of those seen in flight. Hence the emphasis on perceptual fidelity.

The physical correspondence between simulator and aircraft in terms of cockpit layout, instrument, controls, etc. for training simulators should result in high equipment cue fidelity. Environmental cue fidelity is of paramount importance for phase II and III approved training simulators [2]. Research and development simulators should possess high environmental cue fidelity, while equipment cue fidelity may be less importance here. The requirements for equipment and environmental cue fidelity [10] are shown in Fig. 6.

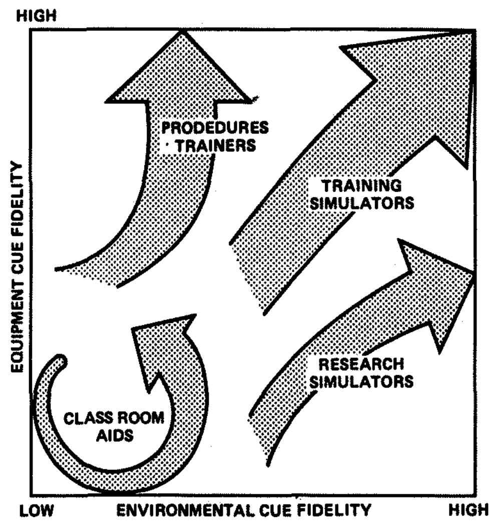

Fig. 6: Requirements for equipment and environmental cue fidelity [10].

With the introduction of Electronic Flight Instrument Systems (EFIS) based on the ARINC 700-series specifications, actual flight hardware is applied in flight simulators. The necessary adaption of this airborne equipment [5] for flight simulators has already been mentioned in Section II.2.
One of the most sensitive elements in terms of fidelity requirements are the primary flight controls in the simulator. The force levels and dynamic fuel perceived by a pilot in control of an aircraft must be totally reproduced in the simulator, to provide high equipment and environmental cue fidelity. The forces felt by the pilot are a combination of spring force, spring gradient, break-out force, control column intertia, forces due to aerodynamic hinge moments, static friction, coulomb friction, viscous friction and dead-bank.
Todays control loading systems based on hydraulic actuators with hydrostatic bearings [1] have demonstrated impressive capabilities to actually provide the precise forces calculated in the mathematical model of the control force characteristics. Primary flight control force models may be identified from dynamic flight test manoeuvres in a similar way as the aircraft mathematical models [11], see Fig. 7, using high accuracy flight test instrumentation equipment.

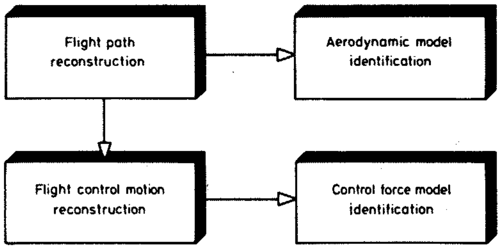

Fig. 7: Distinct steps to identify aerodynamic and control force models [11].

Future aircraft may be flying under control of the autopilot, autothrottles and Flight Management Systems 95% of the time. The maintenance of the pilot's manual flying skills and the training of abnormal and emergency procedures, using advanced flight simulators, will require more and more attention [14].
NASA Langley and NASA Ames Research Centers initiated, in cooperation with Lockheed Georgia, the development of Advanced Concepts Research Simulators [12]. These flight simulators will be used to evaluate flight deck concepts [13], human-engineering aspects and operational procedures. One of the envisaged cockpit designs is shown in Fig. 8.

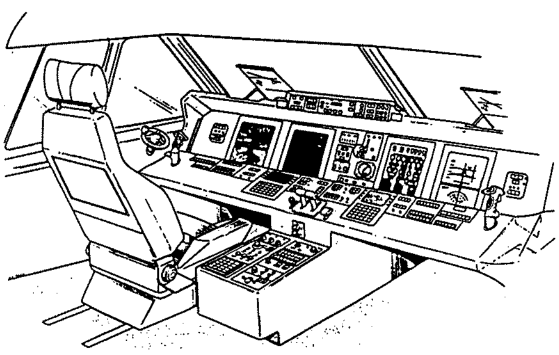

Fig. 8: Advanced concept flight station.

The purpose of the research program carried out using the Advanced Concept Research Simulators will be the evaluation of:
- Future aircraft operation techniques;
- New display technology and criteria;
- Flight station integration;
- Flying qualities and control systems;
- Crew performance and associated human factors aspects;
- Flight hardware and system reliability.

More complex interfaces between the pilot and the aircraft systems, e.g. 'touch panels' [13], are introduced which also impact training, as the controls can no longer be identified by location and shape.

II.4. Visual systems

In piloted flight, vision is the primary sensor for the derivation of real world data. Even today, with the availability of many sophisticated instruments, systems and automatics, vision still plays a crucial role in the piloting task. In flight simulation visual systems are equally important. Out-of-the-window visual simulation presents a formidable challenge because of the fantastic performance capabilities of the human eye [15]. The central foveal area of the retina, having a resolution better than 1 arc min., answers the question of 'what' of pattern vision and the peripheral retina, having a resolution of about 20 arc min and being highly sensitive to image movement, answers 'where' the observer or the environment are moving. The field of view limits of human vision are:
- Fixed head and eyes: foveal 5° diameter; peripheral 190°H x 113°V.
- Moveable head and eyes: foveal 144°H x 170°V; peripheral 474°H x 170°V.

Other perceptual capabilities of human vision, i.e.: luminance/brightness, contrast, acuity and colour are outside the scope of the present paper and can be found in the literature [16]. Together with the other body senses, see Section II.5, the visual sensory system provides a visual/vestibular/kinesthetic interaction, which plays a vital role in the perception and control of motion in a closed loop control task.

Over the past 30 years a wide variety of visual simulation systems have been conceived and developed and many of these are in use today.
The visual systems which are currently available and most widely used are:
- Modelboard systems, using closed circuit television (CCTV) or a laser camera and laser projector.
- The shadowgraph system, using point light sources shining through transparant models.
- Computer generated image (CGI) systems, using a beam penetration colour CRT, a TV monitor, a TV projector or a laser projector for presentation.

Some of the typical components of visual systems and the combinations of these components that have been employed are shown in Fig. 9.

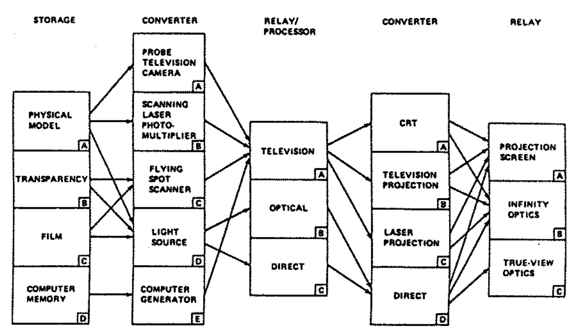

Fig. 9: Components of visual systems and some of the various combinations [16].

Modelboards still offer the richest scene content but have fundamental limitations on operating volume. Consequently several modelboards are required to cover a reasonable operating volume, occupying a lot of space and incurring high running costs. The introduction of the laser camera system improved resolution and it may provide adequate depth of field by dynamic focussing.
The shadowgraph has an even more limited model then the modelboard. Therefore, shadowgraphs are of value only for special applications, such as the current sky/ground projectors, and possibly for generation of a large field of view for helicopter operations in and around hover [17].

CGI-data bases presently lack detail content, but rapid advances are being made. Realistic texture, assists the pilot in perceiving his own motion relative to the outside world, providing velocity vectors in the visual scene. It enhances the sense of proximity to inclined and vertical surfaces and offers the prospect that all the picture content needed for training, updated at an acceptable rate, may be available in the near future. A functional block diagram of a typical CGI-system is presented in Fig. 10.

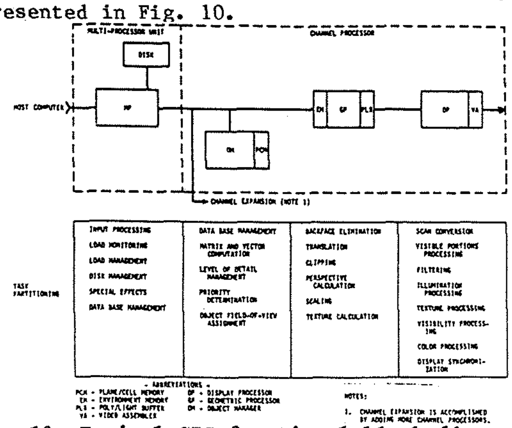

Fig. 10: Typical CIG functional block diagram.

For display devices field of view and resolution are, for one channel and a given bandwidth, inversely related. The most common display device is the television monitor. It has a resolution of about 3 min arc on a 60° diagonal field of a 1000 line TV display. The calligraphic display, generally combined with raster insertions for specific features, e.g. runway markins, horizon glow, etc., is an alternative to the conventional TV raster format. The resolution of these displays is generally better than TV resolution, but a limited colour spectrum is available, using a beam penetration CRT. A full colour calligraphic projector is available, however, and several of them can be combined to give a wide angle, collimated field of view. The laser projector offers significant improvements over current systems in both field of view and resolution [18], primarily by virtue of its 100 MHz bandwidth. These projectors may be used with either model-board or CGI-systems, see Fig. 11.

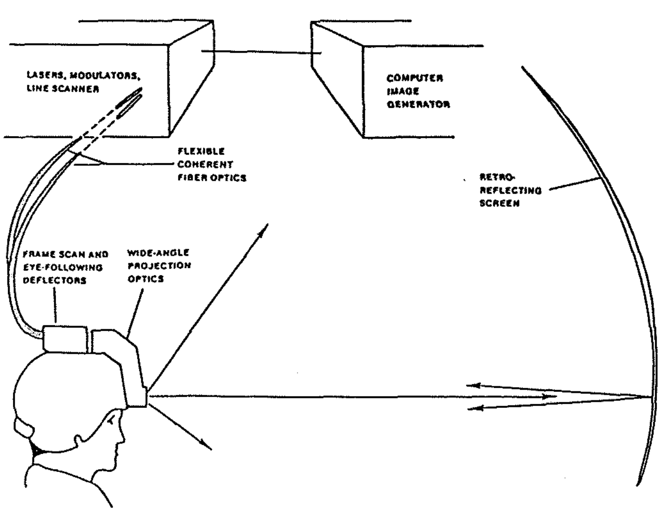

Fig. 11: Helmet-mounted laser projector concept.

An urgent need exists for improved display devices to take advantage of improvements in CGI-systems. New techniques are being developed, e.g. matrices of LED or LCD and liquid crystal light valve projectors, the latter achieving 1 min arc resolution over a small and 4 min arc over a large field of view. FAA-phase I, II and III [2] visual system requirements are presented in Table 1.

II.5. Motion systems

Non-visual perception of motion relies on the subsequent human sensors, see Fig. 12:

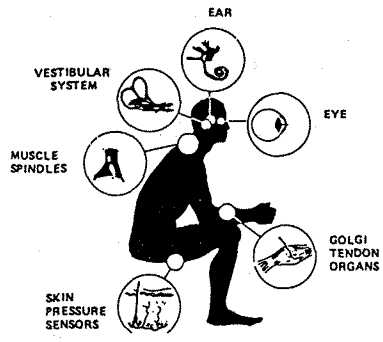

Fig. 12: The human sensors.

1. The vestibular system, containing the semicircular canals and the otoloths. The semicircular canals are fundamentally overdamped angular accelerometers, but their function is more analogous to that of rate gyros sensing angular velocity of the head about any axis. However, at frequencies below 0.1 Hz, which are quite common in airplane motions, the semicircular canal signals rather exhibit a phase lead making them closer to indications of angular accelerations [10]. The otoliths play the role of linear accelerometers, sensing specific forces along any axis. Like any linear accelerometer, they are incapable of distinguishing between gravitational acceleration and linear acceleration with respect to inertial space.
2. The pressure sensors, consist of both surface tactile receptors in the outer layers of the skin, and deep pressure sensors located well below the surface. They add the otoliths in sensing specific forces and their output forms the basis of 'flying by the seat of the pants'.
3. The proprioceptive and kinesthetic senses signal to the central nervous system the relative positions of parts of the body, as well as their movements. Three basic types of sensory mechanisms are involved. The muscle spindles sensing muscle length and the Golgi tendon organs sensing muscle tension. The combination of the proprioceptive senses permits subjects to perceive specific forces, acting on the body.

The non-visual sensors are less precise than the visual sensory system. However, they respond more rapidly and do not require direct attention of the subject. The characteristics of the non-visual sensors permit the generation of motion in a very limited space, using cockpit motion systems, see Section III.

Faithfull reproduction of aircraft motion needs large travel of the motion system. Therefore research institutes like NASA Ames and RAE use very large travel systems in their research and

development simulators [19,20]. The major users of motion systems, the airlines, apply for their training simulators so-called synergistic motion systems. The six actuators with a travel of about 1.50 m each, used in these motion systems, have been provided with hydrostatic bearings [1] since 1977. This development resulted in large improvements in the dynamic characteristics [21] of these motion systems. The main criticism of synergistic systems, compared to systems having independent travel for each degree of freedom, is that independent systems can achieve the full travel in all axes simultaneously, whereas synergistic systems suffer severe restrictions if axes are used in combination.
British Aerospace, Warton acquired a small synergistic 6 DOF motion system with a jack travel of about 0.6 m for their research and development fighter simulator [22]. The aim is a compact installation with good dynamic performace to simulate small responsive aircraft. The primary functions of the translational modes of the motion system are to simulate vibrations (buffet, runway roughness, turbulence, etc.). The rotational modes provide initial angular accelerations and the change in gravity vector with aircraft attitude.
Hydraudyne Systems & Engineering, Boxtel, the Netherlands is currently producing a second generation hydrostatic motion system for the National Aerospace Laboratory, NLR, in Amsterdam. The advanced technology actuators, used in this motion system, have a travel of 1.85 m. They are designed in cooperation with Delft University of Technology [1]. By mounting a spine in the actuators, lower and upper piston areas are kept equal, resulting in symmetrical flow for accurate control, and higher lateral stiffness.

In the next section the generation of high fidelity 6 DOF motion cues will be discussed.

III. Motion cue generaton

III.1. General

The generation of motion cues in flight simulation is based on, see Fig. 13.

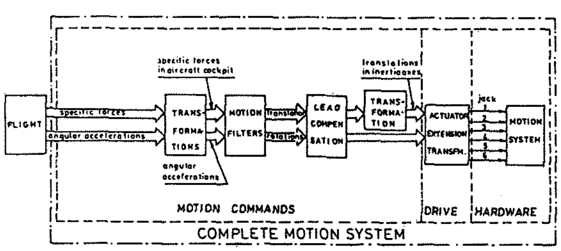

Fig. 13: Basic elements of motions cue generation.

1. The motion system hardware and in particular its dynamic characteristics, see Subsection III.2.
2. The motion drive software, controlling simulator cockpit motion and as a matter of fact generating the 'motion cues'.

Before starting to elaborate on the generation of motion cues, it may be appropriate to present a definition of a 'cue' and to specify what types of cues are important in flight and flight simulation. A definition of a cue may read: 'A cue is a cluster of sensory stimuly -acting on the pilot via any of his sensory channels - closely correlated with a characteristic of the aeroplane and its behaviour, which is relevant to the pilot when flying the aeroplane' (in Webster's Dictionary, a cue is called a feature indicating the nature of someting perceived). Relevant types of cues in flight and flight simulation may be distinguished, according to Subsection II.3, as follows:

1. Environmental cues, which may be subdivided in:
   - 1.a. Alerting cues, due to the initial effects of disturbance motions, like the aeroplane's response to turbulence, runway rumble, engine failure, etc.
   - 1.b. On-set cues, due to the initial effects of pilot-generated motions immediately after the start of a manoeuvre.
   - 1.c. Sustained cues, due to the prolonged or quasi-static effects of both disturbance motions and pilot-generated motions.
   - 1.d. Transient cues [23], covering the time-span between on-set ($t = 0^+$) and sustained cues (t = large).
2. Equipment cues, which confirm to the pilot that he is in actual flight and motivate him to behave accordingly. It may well be, that the transient, systained and equipment cues all fulfill a similar function. Together these cues might be called 'confidence cues'.
3. False cues, occur in piloted flight simulation only. They are clusters of sensory stimuli resembling any of the above cues, but they are <u>not correlated</u> with the corresponding aspects of the aircraft's characteristics. The <u>absence of a cue</u> expected by the pilot on the basis of his internal model [24], providing an a-priori estimate of the variables the pilot is paying attention to, is also considered as a false cue.

In Subsection III.3 the generation of drive commands controlling simulator cockpit motion will be discussed. Flight simulator critical manoeuvres, which are used to compare the motion cues in the aircraft cockpit to those in the simulator cockpit, are presented in Subsection III.4.

III.2. Dynamic characteristics of the motion system hardware

High fidelity 6 DOF motion cues are generated, using a balanced combination of motion system hardware and drive software, see Fig. 13. Before this software can be optimized to control a specific motion system, its dynamic characteristics should be measured and documented in detail. A systematic, uniform method to do this has been published by AGARD in 1979 [21], and is briefly summarized here.
The recommended motion system characteristics [21] to be measured are:
- Excursion limits for single degree of freedom operation.
- Describing functions (Bode plots) for each degree of freedom for the uncompensated as well as the lead compensated motion system.
- Linearity and acceleration noise [1].
- Hysteresis.
- Dynamic threshold (output acceleration time delays) [10].

The above measurements are performed, using standardized sinusoidal and step input signals, respectively. For a hydraulic motion system with hydrostatic actuators, correctly compensated for dynamic lag, a bandwidth of 6 Hz, an acceleration noise level of 0.01 g and a dynamic threshold of less than 50 msec can be obtained in each degree of freedom.

A software package, to perform the measurements according to AGARD [21], was developed for the DUT 3 DOF motion system on an EAI Pacer 600 hybrid computer. This program [25] is currently being transferred to the GOULD SEL 32/87 computer and extended to 6 DOF. The program generates the standardized input signal which drives the motion system after Digital to Analog Conversion. Accelerometer outputs, measuring the motion system response, are filtered by analog pre-sampling filters before Analog to Digital Conversion. Forcing function update and motion system response sampling are carefully synchronized by using the same clock-pulse.

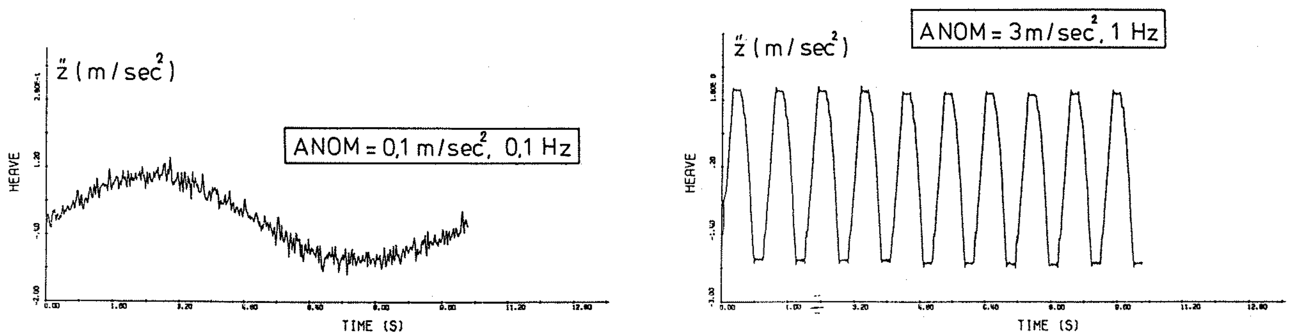

Fig. 14: Reconstructed time histories of heave acceleration.

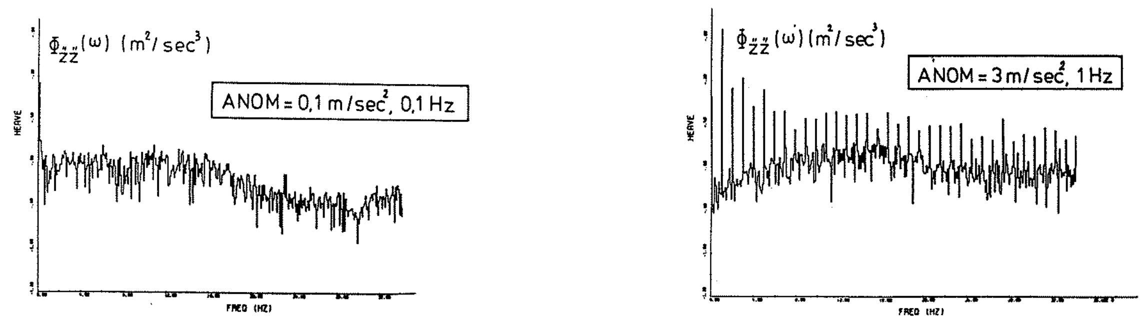

Fig. 15: Heave acceleration power spectra, sinusoidal heave inputs.

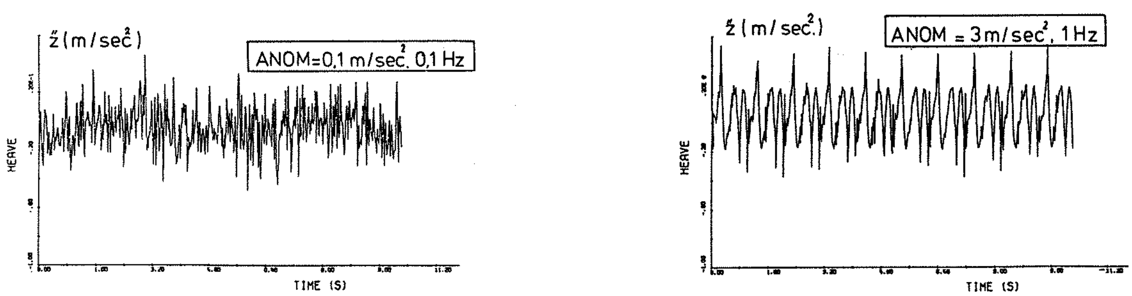

Fig. 16: Reconstructed time histories of heave acceleration noise.

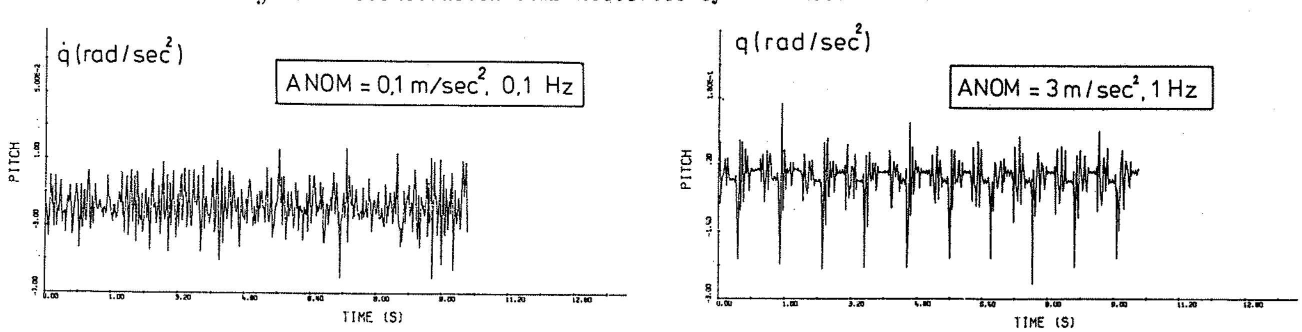

Fig. 17: Reconstructed time histories of parasitic pitch acceleration, due to sinusoidal heave input.

Of the complete motion system dynamic performance measurements [25], only a few examples are presented here.

Fig. 14 shows two examples of measured heave acceleration response, at 0.1 Hz with the input acceleration amplitude (ANOM) at 0.1 m/sec^2 (about the threshold of perception), and at 1.0 Hz with ANOM = 3 m/sec^2. The latter heave acceleration response clearly shows the deformation of the input sinusoid, due to the system limits (max. output acceleration is 2.22 m/sec^2). The corresponding power spectra are presented in Fig. 15.

Heave acceleration noise and parasitic pitch angular accelerations are shown in Figs. 16 and 17 for both cases, respectively. Apart from these plots, the software package also generates a rather complete printout featuring the subsequent items:

- Gain and time constants of the pre-sampling filters.
- Standard deviations of the fundamental frequency, the acceleration noise and the parasitic accelerations.
- Peak accelerations in each degree of freedom.
- Amplitude ratio and phase shift of the describing function.
- Peak ratio (r_p), noise ratio (r_n) [21] and nominal versus actual accelerations, velocities and displacementys in the driven degree of freedom.

The software package can also be applied to identify the dynamic characteristics of the complete motion system, including the motion filters, see Fig. 13. In this way, the frequency range for 'high fidelity motion' [19], where phase distortion should be less than 20° (either lead or lag), can be determined. Presently, a study on this topic entitled 'Simulator Characteristics and Perceptual Fidelity' [26] is in progress.

III.3. Motion drive commands controlling simulator cockpit motion

The generation of adequate motion cues in a limited space is based on the characteristics of the non visual sensors, in particular the semicircular canals and the otoliths, see Subsection II.5. They only function as adequate transducers of angular velocity and specific force, respectively, over a limited frequency range. Therefore simulator cockpit motion needs to match aircraft cockpit motion only within this range. In particular the low-frequency characteristics of the semicircular canals and the otoloths, below about 0,1 Hz [10] makes it possible to 'wash out' motion platform tilt and linear acceleration, respectively, by slowly returning the platform to its neutral position, without allowing the pilot to detect this motion disparity. The efficiency of so-called washout algorithms (motion filters) depends on the effective thresholds [27] of the semicircular canals and otoliths and their respective responses to different combinations of accelerations and velocities. The use of vestibular models [28] to match simulator cockpit motion to aircraft cockpit motion is a well known approach.

Sustained linear acceleration can not be achieved in a limited motion simulator. But the graviceptors, including the otoliths, are incapable of distinguishing between linear acceleration and gravitational acceleration with respect to inertial space. Therefore steady pitch or roll attitude (tilt) of the motion platform is used as a substitute for sustained linear acceleration. Care should be taken, however, that the rate of pitch or roll, utilized in performing the 'g-tilt', be such as to avoid the generation of inadvertent false (rotation) cues. By rolling or pitching at slightly super-threshold rates to tilt angles less than ideally required, compromises are being achieved to minimize the generation of false cues. Visually induced motion sensations using peripheral vision [29] may be a partial substitute for non-visual motion cues.

Over the past 15 years several types of motion drive algorithms have been developed [30]. The most common forms of these algorithms are:

- linear second-order high and low pass filters, currently applied in airline flight simulators;
- coordinated adaptive washout, applied in some research simulators;
- the optimal control approach, applied a.o. to the Vertical Motion Simulator (VMS) at NASA Ames [28].

As an example, the motion drive algorithms currently applied at DUT, to synergistic 6 DOF motion systems, are briefly described. These algorithms use higher order linear filters supplemented by non-linear elements, depending on the motion system excursion limits and the simulator task. The drive algorithms perform the following basic operations:

1. The aircraft angular roll, pitch and yaw accelerations to be simulated are both limited and high-pass filtered, to generate the alerting and on-set angular motion cues.
2. The specific force errors (false cues), generated as a result of the simulation of the above roll and pitch accelerations, are corrected using lateral and longitudinal motion platform linear accelerations, respectively. In this way the specific force error, in e.g. coordinated turns, is kept below the pilot's perception.
3. The specific forces along the X, Y and Z aircraft body-axes are transformed from the aircraft c.g. to the centroid location of the motion platform [31].
4. Both the specific forces at centroid location and the specific force errors along the X and Y body-axes are limited and filtered by higher order low-pass and high-pass filters. The low-pass filter outputs generate sustained longitudinal and lateral specific forces using motion platform tilt. The high-pass filter outputs generate the alerting and on-set longitudinal and lateral linear motion cues. The specific force along the Z body-axis is high-pass filtered, allowing the simulation of its high-frequency content only.

Provisions are being made, that specific forces and angular accelerations result in simulator displacements only, if they are above the effective threshold levels of the pilot's perception. The resulting translations and rotations of the motion platform are lead compensated for the dynamic lag of the motion system hardware, see Fig. 13. After transformation of the platform translations to inertia axes, the actuator extension transformation calculates the length of each of the six motion system hydraulic jacks.

As an illustration of the above the performance of the motion drive algorithm is shown in Fig. 18. The aircraft simulated in this example is a jet transpoirt aircraft in the approach configuration. From top to bottom in Fig. 18, the rudder input

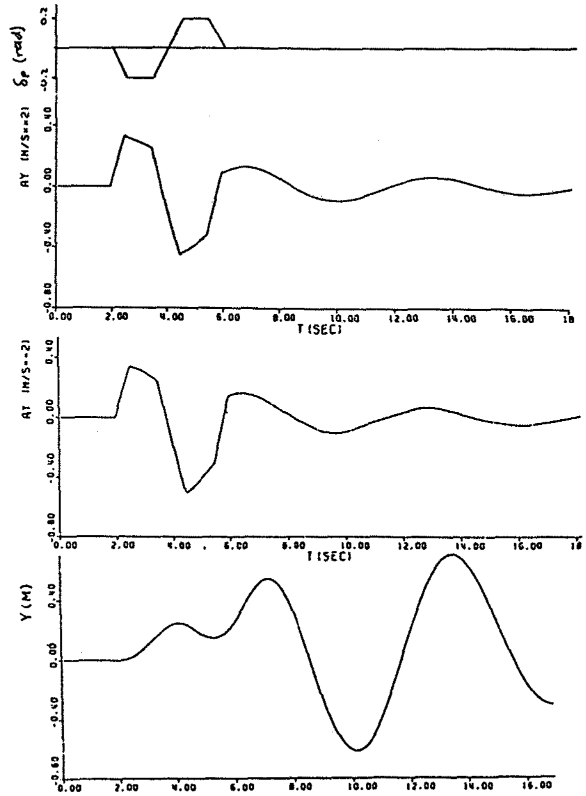

Fig. 18: The generation of lateral specific force, using DUT motion drive algorithm.

(δ_p), the lateral specific forces in the aircraft cockpit (AY), the lateral specific force in the simulator cockpit and the lateral displacement of the motion platform (Y), are presented. Comparison of the lateral specific forces in the aircraft and the simulator cockpit shows the almost perfect lateral specific force simulation obtained, using only limited lateral simulator displacement. Time delays for the alerting and on-set motion cues, generated by the above algorithms, are kept below 80 msec by using a 30 Hz computer update rate and a high-bandwidth, lead-compensated hydrostatic motion system.

III.4. Flight simulator critical manoeuvres

As mentioned already in the introduction, differences between the behaviour of the aircraft and the ground-based flight simulator will remain. Very often, the simulator will be more difficult to fly than the aircraft, as a consequence of reduced environmental fidelity, time delays, etc. As a result, pilot performance for some manoeuvres in the simulator may be inferior relative to the performance for the same manoeuvres in real flight. Such manoeuvres, which tax both the pilot and the simulator to the utmost, may be called: 'Flight Simulator Critical Manoeuvres'. Clearly, the exact type and shape of the critical manoeuvres depend on the application and task of a particular flight simulator. Obviously the objective fidelity of the simulator will be compromised, during these manoeuvres.

An important application of Flight Simulator Critical Manoeuvres (FSCM) could be the approval of flight simulators to perform certain tasks [2]. Flight simulator operators should identify the most appropriate FSCM's for their particular simulator and task, whereafter these FSCM's can be used to optimize the simulator characteristics for maximum perceptual fidelity. Examples of FSCM's, for airline training simulators could be:

- outboard engine failure during take off, just before and after V1,
- side-step manoeuvre in the final approach to landing,
- turns, in the air as well as on the ground during taxi,
- go around with one engine failed,
- accelerated stop (aborted take off).

Suitable chosen and agreed FSCM's could also be used as the basic input manoeuvres in the Approval Test Guide [2] (ATG) for a particular flight simulator.

IV. Concluding remarks

Real-time flight simulation technology has reached the level, where the aircraft dynamics in the air, as well as on the ground, can be simulated with the fidelity, required for 'Total Simulation'. Necessary prerequisites for this purpose are:

* A well developed data base of the aircraft handling characteristics.
* An extensive aircraft mathematical model, wherein the data base fits.
* Sufficient computer power to satisfy the required computational duty cycle as a function of aircraft natural frequency.
* Adequate objective fidelity in the simulator cockpit to represent the character and workload of the pilot's task as it is in flight.
* A visual system, which has sufficient resolution and an adequate collimated field of view.
* A complete motion generation system, optimized for maximum perceptual fidelity.
* Maximum latency, in particular for motion cue generation, less than 50 msec.

Future research efforts in the area of flight simulation techniques should encompass the following topics:

- Minimum essential visual and motion cueing requirements for a particular flying mission.
- Microprocessor architectures.
- Real-time rotorcraft simulation, in particular rotor modeling and the interaction between main and tail rotor.
- Flexibility of large aeroplanes and the interaction with atmospheric turbulence and windshear.
- Flight simulator critical manoeuvres for particular simulator applications and tasks.

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Appendix

The acronyms used for the software modules in the modular program structure of Fig. 5 have the following meaning:

START — Main program unit of task 'MAIN.LM', used for Array-declaration and transfer of data to subroutine MAIN.

MAIN — Control program for non-linear aircraft simulation.

MODL — Motion Drive Laws to control the flight simulator motion system.

VIDL — Visual Drive Laws generating inputs to a C.G.I. visual system.

INSTR — Instruments software interface to drive the flight instruments in the simulator.

INCO — Main procedure of task 'INCO.LM', used to establish a memory area for communication between tasks 'MAIN.LM' with 'INCO.LM' (GLOBAL 05) and INCO.LM with AERO.LM (GLOBAL 06). In the initialization phase, the initial condition is computed (FINCO) and during simulation the integration process is executed (FAIRC).

FINCO — Subroutine computing a steady initial condition using the non-linear equations of motion of the aircraft. FINCO is used prior to actual simulation.

FAIRC — Subroutine computing the aircraft state vector using one of two numerical integration methods: 1. HEUN; 2. RUNGE-KUTTA (4th-order).

FSIDS — FSIDS provides a survey of the input data for subroutine MAIN and specifies the descriptors of the aircraft variables.

FINER — Subroutine computing the inertia parameters in the equations of motion in a form where all time derivatives appear in the lefthand side of the equations.

FSTAT — Subroutine computing the air density at a given flight altitude, using the model of the 'US Standard Atmosphere'.

INPUT Z-CARD — The 'Z-CARD' is the I/O-interface between the Gould SEL 32/87 and the flight simulator systems. The routine INPUT Z-CARD converts 32-bit reals into the correct output format.

OUTPUT Z-CARD — This routine converts the input from the flight simulator systems into 32-bit reals for the Gould SEL 32/87.

AERO — Main procedure of task 'AERO.LM', used to establish a memory area for communication between tasks 'INCO.LM' with 'AERO.LM'.

FDERI — In this subroutine the augmented state time derivatives of the aircraft are computed, using the aerodynamic model (FAER4), the engine model (FENG4) and the landing gear model (LAGM4).

FCOMY — In this subroutine the airspeed V, the angle of attack α, the sideslip angle β, the angle of climb γ, the climb (descent) rate C and the flight altitude h are computed from the state vector x(t) and presented in the output vector y(t).

FAER4 — This subroutine calculates the aerodynamic forces and moments acting on the aircraft (the number indicates the aircrafttype).

FENG4 — This subroutine computes the dimensionless forces and moments resulting from the operation of the aircraft engine(s).

LAGM4 — This subroutine calculates the forces and moments of the landing gear on the aircraft during taxi, take-off and touchdown.

FDBRD — This subroutine reads a matrix or vector from a database, containing for example the lift coefficient (C_L) as a non-linear function of angle of attack (α), flap position (δ_f) and Mach-number (M).

FTABINT — This subroutine performs a linear table interpolation in tables with dimension of either M*N or 1*N.